CR -124116

Development of a Plan for Automating Integrated Circuit Processing

Final Report

Contract No. NAS8-26909

Contract Dates 1 March 1971 - 1 December 1971

Contract Amount $23,195.00

Prepared for

George C. Marshall Space Flight Center

National Aeronautics and Space Administration

Alabama 35812

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SECTION I

1.0   INTRODUCTION

This report includes the operations analysis and equipment evaluations pertinent to the design of an automated production facility capable of manufacturing beam-lead CMOS integrated circuits. The overall plan shows approximate cost of major equipment, production rate and performance capability, flexibility, and special maintenance requirements. Direct computer control is compared with supervisory-mode operations. The plan is limited to wafer processing operations from the starting wafer to the finished beam-lead die after separation etching.

Several appendices are included to illustrate the extent of work already accomplished in implementing various automation schemes, and the type of equipment which can be found for "instant automation." The plan is general in nature, so that small shops or large production units can perhaps benefit. The equipment reported in this report was selected for study by the Motorola equipment engineering and process development departments, but is not a complete list of available units or suppliers, nor is any recommendation to be construed from the mention of specific suppliers. Examples of major types of automated processing machines are shown merely to illustrate the general concepts of automated wafer processing.

SECTION II

2.0   TECHNICAL BACKGROUND

2.1   CMOS PROCESSING

2.1.1   General

The prime attraction of CMOS for NASA and military applications is the fact that power is consumed only during switching. The making of CMOS involves the ability to construct both p and n islands on the same substrate. In early 1969 a CMOS metal gate production process was established to permit fabrication of a standard product line.

The metal gate process is characterized by the following features:

(1)   Monolithic construction - The starting substrate is n-type material into which a lightly doped p "tub" is diffused for the later construction of n-channel devices.

(2)   Low threshold voltage - Through the use of <100> material and ultra-clean, low Q_{ss} processing, the thresholds of both n- and p-channel devices are in the range 1.7 to 2.0 volts.

(3)   Low leakage - Special processing techniques have reduced the leakage currents to extremely low levels. The typical quiescent power supply leakage for two 4-input NOR gates is 1×10^{-9} amperes at 10 volts.

(4) <u>Excellent threshold stability</u> - Devices from the standard production process have been stress tested at ±15 volts and 225°C for 500 hours with an average threshold shift, under either positive or negative bias, of less than 0.15 volt.

(5) <u>High breakdown voltages</u> - The typical V_{DD} breakdown voltage of the standard circuits is 30 volts. This means the circuits can be safely operated at supply voltages of 20 to 25 volts.

In addition to the above standard process, Motorola has developed a self-aligning, silicon gate complementary MOS process for use at very low supply voltages. Threshold voltages of 0.7 to 0.9 volt can be achieved for both the n- and p-channel devices in a single chip.

More details on both the metal-gate and the silicon-gate processes are included in the following sections.

2.1.2   <u>Metal-Gate CMOS Process</u>

The starting material used in Motorola's CMOS process is 5 ohm-cm, <100>, n-type silicon. A 10-micron deep 1000 ohm/sq p^- region is diffused into the substrate to form a "tub" for n-type devices. A high concentration p^+ region is diffused into the n-type substrate to form the source and drain of the PMOS. For NMOS, the source and drain is formed by a n^+ diffusion in the p^- isolation region. The gate oxide of 1000 $\overset{o}{A}$ is thermally grown after the silicon surface is treated with a special chemical clean. Aluminum metallization is used for the gate electrode and contacts to the diffused source-drain. The existing process gives a threshold voltage of $2.0 \pm {}^{0.2}_{0.3}$ volts for both PMOS and NMOS devices.

2.1.3   Silicon Gate CMOS Process

The starting material is p-type <100> silicon whose resistivity falls in the range of 1 to 4 ohm-cm. The actual doping level is determined by the threshold voltage desired. Devices that have been fabricated indicate that the effects upon the threshold voltage of the interface charge (less than or equal to $10^{11}/cm^2$) is small and consistent, and thus can easily be compensated for by a judicious choice of the starting resistivity. Resistivity is controlled within 20 percent to achieve the required threshold voltage.

The wafer is then oxidized to a thickness of 0.5 to 1.0 micron and the oxide selectively removed in those areas in which the p-channel devices are to be fabricated. Silicon is then removed through these openings by controlled KOH etching and the holes epitaxially refilled with n material. The resistivity of the backfill material will fall in the range of 2 to 5 ohm-cm and the doping level controlled to within 30 percent. After polishing back to a smooth uniform surface, the wafer is ready for fabrication of the actual devices.

The wafer (which now contains n-type and p-type regions) is then oxidized to a thickness of approximately 5000 Å, primarily to reduce the capacitance of the gate bonding pads and to provide an edge for the diffusion cuts. This oxide is then removed in the source, gate, drain, guard and scribe regions.

Next the gate insulator is formed by thermal oxidation. It has been found that in situ HCL etching and subsequent oxidation, both in an epitaxial reactor, produce an extremely uniform surface and a stable, drift-free oxide.

This step is followed by a polycrystalline silicon deposition in a low temperature (650°C) furnace. This produces an extremely fine-grain film that can be patterned with conventional photoresist techniques to produce gate widths as small as 0.1 mil.

The gates are then patterned by removing all the poly-silicon except in the region of the gates and associated bonding pads. A low temperature glass deposition follows, which serves to protect the n-channel devices during the p=channel diffusion. The glass is removed in the areas that require a p-diffusion, p-channel source and drain, p-channel gate, and n-channel device guard ring. This cut is made with a self-aligning wash-out approach and the edges of the cut are defined by the silicon gate and the thick oxide step left prior to the formation of the gate insulator.

The wafer is then diffused, with p-type impurity, forming sources, drains, guard rings, and doping the polysilicon gates of the p-channel units.

A similar glass deposition, patterning, the n^{+} diffusion form guard rings on the p-devices, n-channel sources and drains and dopes the gates of the n-units.

A third glass deposition follows which is of sufficient thickness to reduce the capacitance of metal interconnecting leads and passivate the surface of the n diffusion. This step can contain a layer of Si_3N_4 to permanently seal the chips against contamination.

Preohmic openings are then cut to the sources, drains, substrates and gates of the individual devices. The wafer is then metallized and patterned by standard techniques. A passiva-

tion step consisting of a low temperature glass deposition and opening the bonding pads completes the front preparation of the wafer.

The complete device then appears similar to the cross-section given in Figure 2-1 which shows all layers of the final structure. The processing steps are listed below.

1. P wafer with oxide.

2. Cut SiO_2 for n pots.

3. Etch and regrow n epi.

4. Polish back.

5. Clean and grow 5k $\overset{o}{A}$ oxide.

6. Thick oxide cut: active device area, guard area, scribe grid.

7. Apply gate insulator and polysilicon gates.

8. Pattern gates.

9. Deposit oxide.

10. Cut p washout: p-channel S-D, grid, n-channel guards and substrate contacts, and pot (n tub) holder.

11. P^+ diffusion.

12. Deposit oxide.

13. Cut n washout: n-channel S-D, p-channel guards and substrates.

14. N^+ diffusion.

15. Deposit thick oxide or nitride.
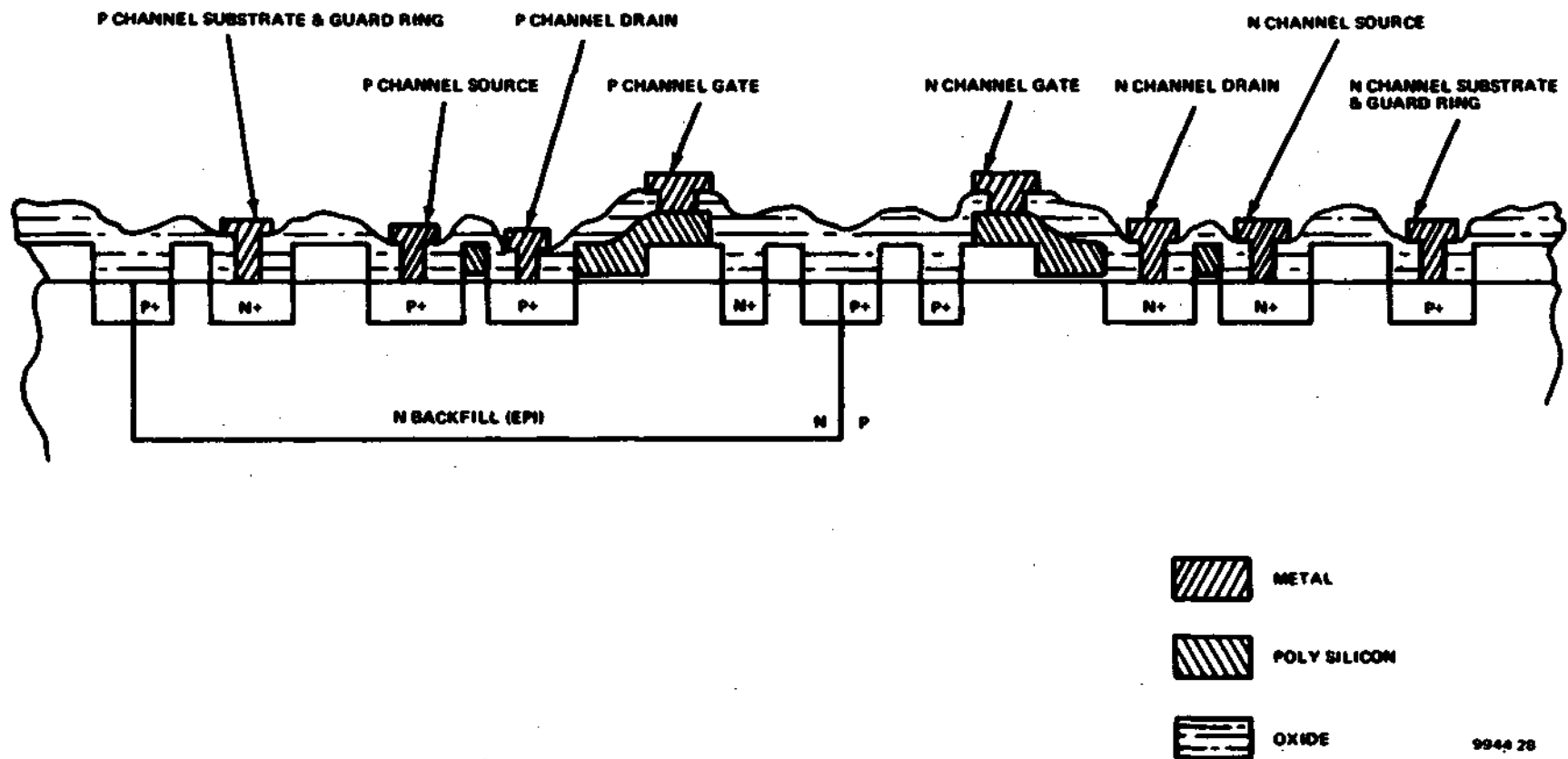
16. Cut preohmic and scribe grid.

P CHANNEL SUBSTRATE & GUARD RING

P CHANNEL SOURCE

P CHANNEL DRAIN

P CHANNEL GATE

N CHANNEL GATE

N CHANNEL DRAIN

N CHANNEL SOURCE

N CHANNEL SUBSTRATE & GUARD RING

P+ N+ P+ P+ N+ P+ P+ N+ N+ P+

N BACKFILL (EPI)   N   P

METAL

POLY SILICON

OXIDE

9944 28

Figure 2-1. Structure of Silicon Gate Complementary MOS Devices

8733-5-0

17. Metallization.

18. Ohmic.

19. Deposit passivation SiO_2.

20. Cut pad apertures and grid.

21. Prepare back of wafer (if necessary for die bond).

It has been found that in addition to having reduced capacitance levels, silicon gate structures are considerably simpler to fabricate. The self-aligning feature of the silicon gate, of course, simplifies the photoresist processing. But in addition, the polysilicon forms a passivating layer that protects the gate oxide against sodium contamination during subsequent diffusion, glass depositions, and metallization steps. This reduced contamination along with the use of identical electrical materials on both sides of the gate dielectric (p-type gates for p-channel devices, n-type gates for n-channel devices) enables the achievement of lower threshold voltages, thereby lower voltage power supply requirements.

2.1.4   Alternate Silicon-Gate CMOS Processes

Alternate silicon-gate CMOS processes use a diffused or ion-implanted tub instead of the epitaxial tub described above. The diffused tub process is simple, but the implanted or epitaxial tubs give improved performance. Implantation for shifting threshold voltage will become a production process this year, and therefore, a pilot implanter was studied.

The Motorola 150kV Ion implanter is a modified "Implanter I" manufactured by Accelerators, Inc. in Austin, Texas. The machine features wafer handling capabilities suitable for pilot

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line production. The analyzing magnet has a mass energy product of 15 at 30 degrees which means atoms as heavy as molybdenum should be implantable at the maximum accelerator energy of 150 keV. If necessary, the beam line could be shifted to a 15-degree port which would allow maximum energy implants of any atom.

The cold cathode ion source currently in use provides a trouble-free beam of 5 microamperes or more of boron or phosphorus at any energy between about 60 keV and 150 keV. The machine is also capable of delivering smaller beam currents of virtually any atom available in a gaseous form. At present, the manifold will allow implants of oxygen, silicon, aluminum, boron, and phosphorus.

Uniformity over the wafer is achieved by scanning the pencil-sized beam over the wafer (limited to 2-inch diameter at present) by means of electrostatic plates which produce a pattern similar to a TV raster. Uniformity from wafer to wafer is achieved by integrating the beam current received by the wafer.

The wafers are held in a 25-position carousel which can be automatically programmed to implant all 25 wafers to the same dose. Chamber pumpdown time is less than 10 minutes and a typical implant suitable for MOS gate threshold shifts, etc. requires less than 30 seconds per wafer so a wafer throughput of at least 40 wafers per hour is anticipated. Heavier implants suitable for source drain contacts or bases of bipolar transistors will take longer and wafer throughput will be correspondingly less.

Automatic handling of wafers from IMS carriers to a modified carousel would complete the mechanization of this process.

2.2   BEAM LEAD SEALED JUNCTION TECHNOLOGY

Beam lead technology involves multiple metallic layers for conductors. The most common method is to sputter Ti and Pt

completing the system with electroplated Au. Some characteristics of this approach are:

(1) While the published reliability information on beam lead technology is not as extensive as that of its wire bonded hermetically sealed predecessor, the results of work performed by Bell Labs, Motorola and others indicate that a more reliable product will result. In addition, considerably more reliability information is available on this technique than on any other technique that obviates the need for flying wires.

(2) Bonding of beam leaded devices to substrate metallization is accomplished by a gold-to-gold thermocompression bond. This is the easiest and simplest bond to make since reliable bonds result over a relatively wide range of variation in the bonding variable of temperature, pressure and time.

(3) Fabrication of beam leaded devices involves the addition of numerous processes that are not normally required. This affects yield and cost. However, the impetus which beam lead sealed junction technology has experienced in recent years indicates that these costs will not be prohibitive within a very short period of time.

(4) Effective techniques for controlling fabrication processes, for in-process inspection and testing and for screening of wafers, beam leaded die, and completed circuits have been established.

(5) Etching of the silicon to separate the die from the wafer requires that the wafer be lapped to approximately 2 or 3 mils thickness. This is expected to limit the maximum size of die that can be used. A relatively large, thin die would be very fragile and subject to breakage during handling for assembly as well as during dynamic mechanical environments common to space type applications.

(6) Since all of the basic interconnecting conductors from the device junction to the package leads are gold, hermeticity requirements are not as stringent as with other systems.

(7) Faulty dice can readily be mechanically removed and replaced during the hybrid assembly cycle.

In the Bell Labs system of beam lead formation, the first step is application of silicon nitride as a passivation layer. The second step in the process is deposition of contacts. The resulting compound is platinum silicide. The process is well defined and probably will remain the same in any automatic production system.

Metallization presently is titanium, plantinum and gold. Though these metals are costly in bulk, only minute amounts are used. The main disadvantage, however, of beam lead metallization as now practiced is the extreme difficulty of etching platinum. This problem leads to the consideration of:

(1) Chemical or electrochemical system alternative to aqua regia.

(2) Other metallization systems. Two systems are
     presently under investigation at Motorola;
     (a) titanium, tungsten and gold, (b) titanium-
     palladium-gold. These systems offer many of the
     advantages of the present method and are addi-
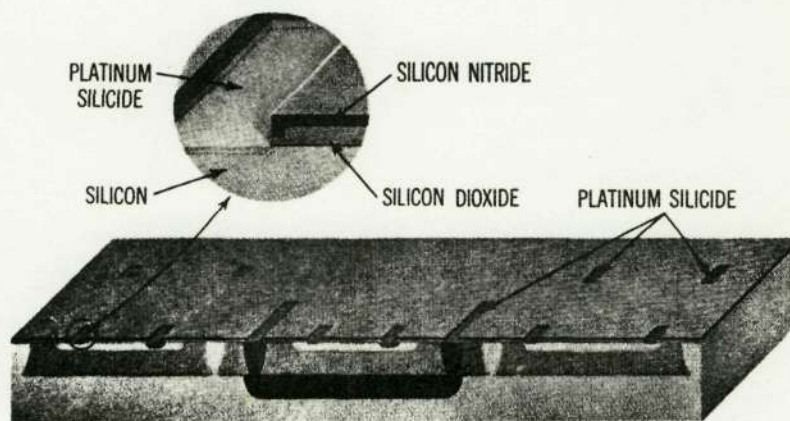   tionally etchable. The disadvantages, if any,
     are being determined.

The effects of platinum sputtering processes on the CMOS
structures are usually disastrous. The palladium evaporation
process solves that problem, but a lower temperature system results.
This question must be resolved in order to design an automated
line for beam-lead CMOS production. Since palladium solves the
etching as well as the sputtering damage problems, the effort is
worthwhile. A parallel effort is needed on etching of platinum
and gentle sputtering.

Figures 2-2 through 2-9 illustrate a typical beam lead
process sequence.

Table 2-I summarizes overall process flow for CMOS
products with beam leads.

2.3   TECHNOLOGICAL FORECAST AND FLEXIBILITY REQUIREMENTS

The basic CMOS-beam-lead materials and methods will
probably evolve into a sequence slightly different from the one
previously described, with ion implantation replacing the tub
diffusion or perhaps thresholds will be adjusted by implantation.
The nitride and polysilicon may in some cases be replaced by
aluminum oxide and refractory metallization or some insulators
and conductors which require novel equipment for deposition and
patterning.

Platinum silicide contact formation.
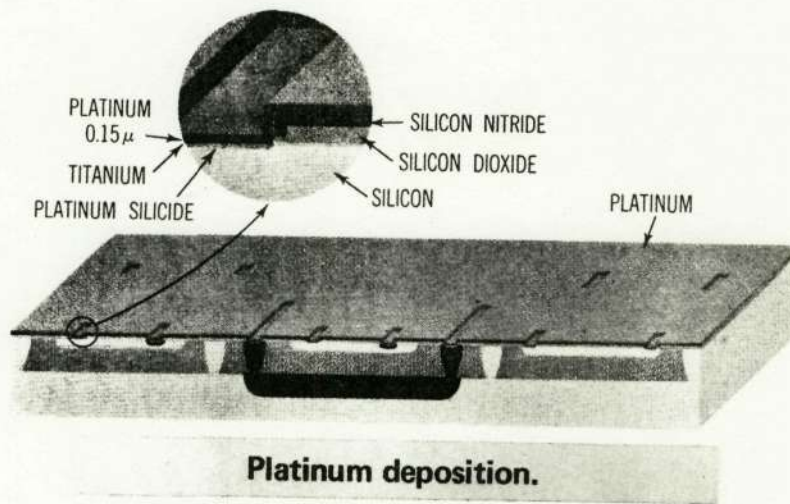
Figure 2-2
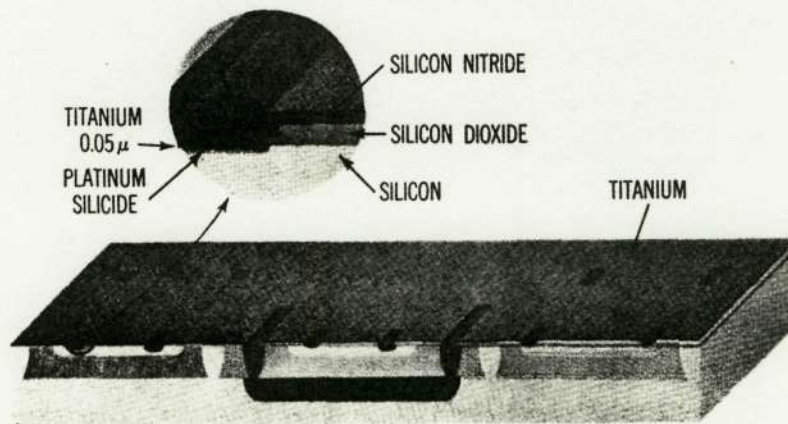
Titanium deposition.

Figure 2-3

PLATINUM
0.15μ
TITANIUM
PLATINUM SILICIDE
SILICON NITRIDE
SILICON DIOXIDE
SILICON
PLATINUM

Platinum deposition.

Figure 2-4

PLATINUM
TITANIUM
PLATINUM SILICIDE
PLATINUM ETCHED AWAY
SILICON NITRIDE
SILICON DIOXIDE
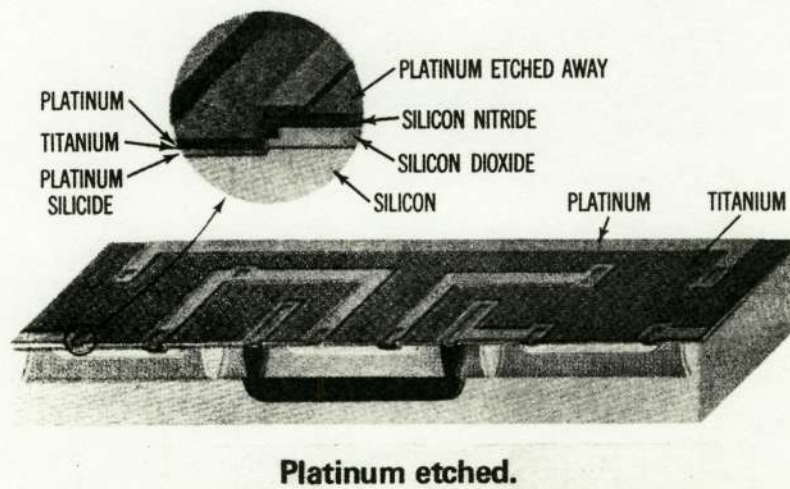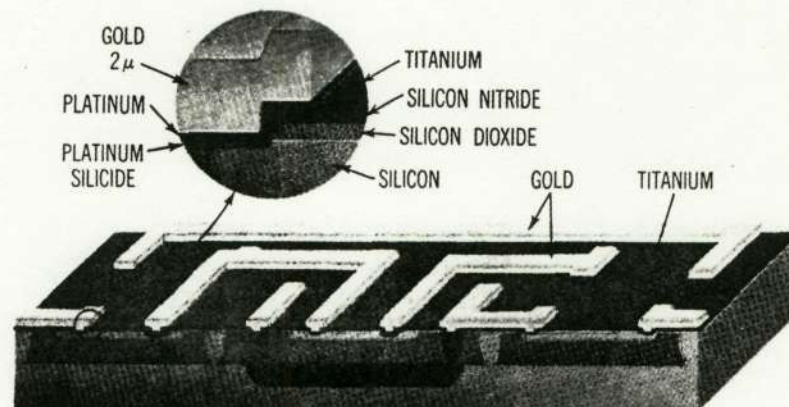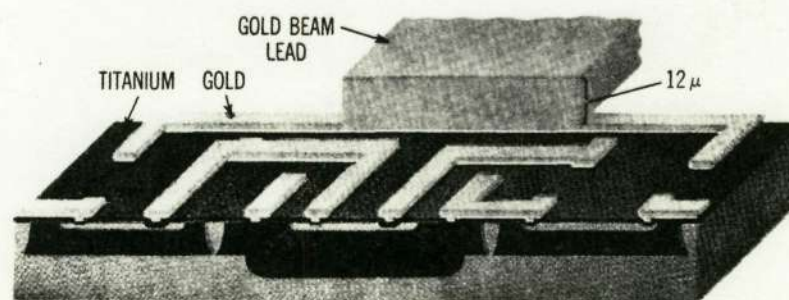SILICON
PLATINUM
TITANIUM

Platinum etched.

Figure 2-5

2-13

First gold (intraconnection) electroplating.

Figure 2-6

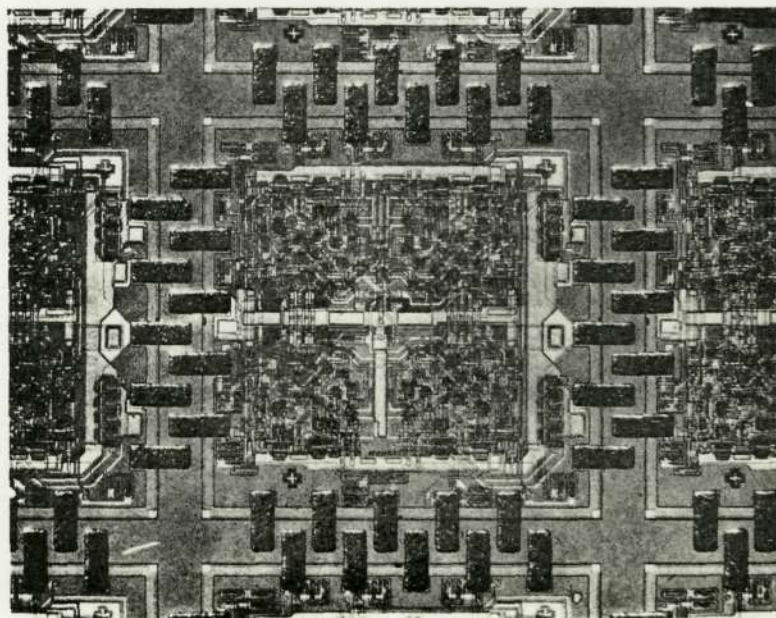Second gold (beam lead) electroplating.

Figure 2-7

GOLD
TITANIUM ETCHED AWAY
PLATINUM
SILICON NITRIDE
TITANIUM
PLATINUM
SILICIDE
SILICON
SILICON
DIOXIDE
GOLD
SILICON NITRIDE
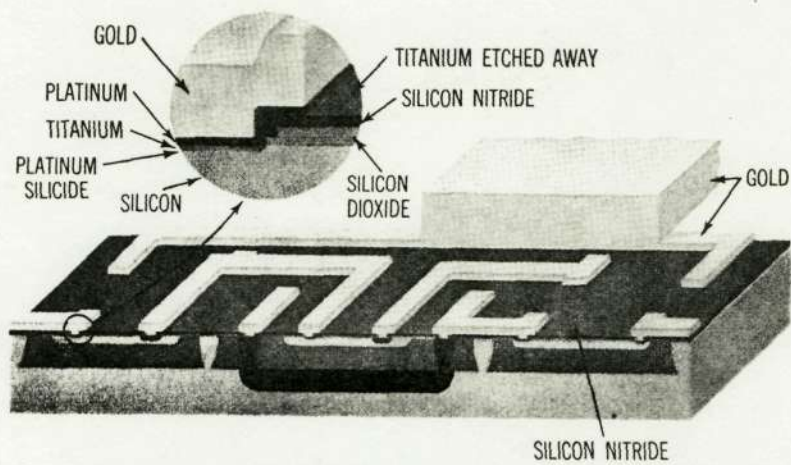
Titanium etched.

Figure 2-8

Figure 2-9 .   Multilayer Beam Lead Metallization

2-15

TABLE 2-I

SUMMARY OF POSSIBLE BEAM-LEAD CMOS PROCESS FLOW

A	Starting material, polished wafer
B	Oxidation
C	First masking to cut tubs
D	Tub diffusion (or implantation, or selective epitaxy)
E	Second masking to cut device regions
F	Gate oxidation and polysilicon deposition
G	Third masking to cut p-channel geometries
H	P^+ diffusion
I	Fourth masking to cut n-channel geometries
J	N^+ diffusion
K	Thick oxide deposition (optional)
L	Nitride deposition
M	Oxide deposition (optional)
N	Fifth mask to cut contact openings
O	Platinum sputtering (or other metal evaporation)
P	Silicide formation (in vacuum or in furnace)
Q	Metal removal
R	Titanium-platinum sputtering (or other metal evaporations)
S	Sixth masking for cutting platinum
T	Seventh masking for defining gold interconnections
U	Gold electroplating
V	Eighth masking for defining beams
W	Thick gold electroplating
X	Titanium removal (or sputter-etch platinum, then etch Ti)
Y	Mount on sapphire and lap
Z	Ninth masking for silicon separation etch (on sapphire)

Near-term technological advances might include:

Ion implantation

Silicon on insulating substrates

Near-contact printing

Projection printing

Optimized positive and negative photoresists

Electron beam align and exposure systems

Automatic alignment to device patterns or small targets

Radiation-hardened structures

Bipolar/MOS compatible structures

Large optimized hybrid structures on silicon or spinel

An automated line must be capable of adjusting to the requirements of new materials and methods, new devices, tighter controls, higher thru-puts, and still be able to reconstruct past performance at will. Modular equipment will allow change; computer control will permit analysis and reconstruction of prior events.

2.3.1   Flexibility Requirements of an Automated Line

The major argument against automation has always been the lack of flexibility given the high rate of change of technology. The MADT was obsoleted before the automation program was actually completed. Mesa transistor manufacturers avoided automation successfully. Integrated circuit makers avoided it, but less successfully. Most companies now agree that selected automation of processing and wafer handling, as well as automatic lot tracking and processing history correlation with probe yields is necessary, but flexibility is mandatory.

2.3.1.1   Wafer Size

The ideal wafer size for a given process step is generally not ideal for all steps. Batch operations do not benefit greatly

by larger wafers, and specially tooled steps such as metallization require careful analysis. The individual wafer steps such as alignment benefit most. <u>There is less pressure to increase the wafer size if the line is automated and predominately batch operations.</u> A manual line with many individual steps will save as much as 40 percent by increasing the size from 2 inches to 3 inches. Subtle yield differences will determine the optimum wafer size. One theory contends that the bad region around the outside of the wafer will be constant while the center good region becomes larger -- thus higher yields with larger wafers. The opposite theory has many supportors. The only way that an automated line can cover the changes which will come is to assure that retooling costs will be minimum. Up to 3 inches in diameter, this is no problem. Four-inch wafers will require complete replacement of about one-third of the equipment now available. Maskmaking limits may prevail to maintain the size to 3 inches for many years. It would be unwise to build a line limited to 2-inch or smaller wafers for CMOS-LSI type circuits unless the volume required was small.

2.3.1.2   Adjusting to New Technology

A line built of modular units which can be removed easily and replaced with updated versions or totally new machines is desirable, but the processing information, equipment parameters, and device parameters must be stored for analysis and perhaps reconstruction of past methods. Thus, the data interfacing with the machines is as important as the modular construction.

A thorough supervisory computer system will monitor and report on key variables, process and device parameters, maintenance history, resultant device yield and characteristics, and supply enough data to an off-line system to allow correlation

studies and other statistical analysis. Thus, new technology can be assessed impartially by tying in to the line for partial utilization until information shows that the benefits outway the risks.

SECTION III

3.0 ANALYSIS AND PLAN

3.1 UNIT OPERATIONS

A listing of basic operations serves to organize the study of equipment and the layout of a facility:

A. Photoengraving (resist coating, mask alignment and exposure, developing, etching, resist removal)

B. Diffusion (furnace operations for oxidations, impurity deposition and redistribution)

C. Chemical vapor deposition (reactor processes in which oxides, nitrides, poly or single crystal silicon, and some metals are deposited from a vapor by a chemical reaction, usually involving heat)

D. Vacuum metallizing (evaporation or sputtering)

E. Electroplating

F. Machining (lapping, grinding, scribing)

G. Cleaning (chemical surface preparations)

One operations strategy might be to physically locate each of these basic types of processing in separate rooms with appropriate facilities for contamination control, maintenance, indirect materials handling and process/product controls. Another strategy would place the individual equipment items in-line according to the present process/product flow. The decision depends on the degree of flexibility which can be built into the line, the money available and thus the equipment utilization required, and, of course, the bias of the management concerned.

3.1.1 Photoengraving

The photoengraving processes have the highest labor content and have received the most attention recently. The alignment of the mask to the wafer is extremely critical and several schemes have been proposed to automate this operation. One of the automatic alignment tools available is shown in Figure 3-1. This machine also incorporates the IMS wafer handling equipment. Details of Computervision application are discussed in two articles included in Appendix A.

The coating and drying equipment manufactured by International Instruments is shown in Figure 3-2. The wafer tray is loaded on the left and indexes through the spinner onto a belt which carries it through the infrared bake oven to an unload station at the right. A similar machine performs developing and baking after exposure.

The automatic alignment process has been tested on MOS-LSI devices at Motorola, and is capable of high quality work (errors less than 1 micron) at a high rate (about 180/hour) with improved mask life (two or three times the normal usage). The process requires special alignment aids stepped into the device array at two places on the mask. A new aid is required for each fine alignment step; thus, four aids are used for normal PMOS processing, up to 12 aids for some bipolar LSI devices. Mask-making errors can be adjusted for, but mechanical shifts limit the accuracy in a production environment.

3.1.2 Diffusion

The control of temperature and gas flow rates has been automated for some time with proportional controllers, mass flow meters and timers. Programmers for valve sequencing are in use
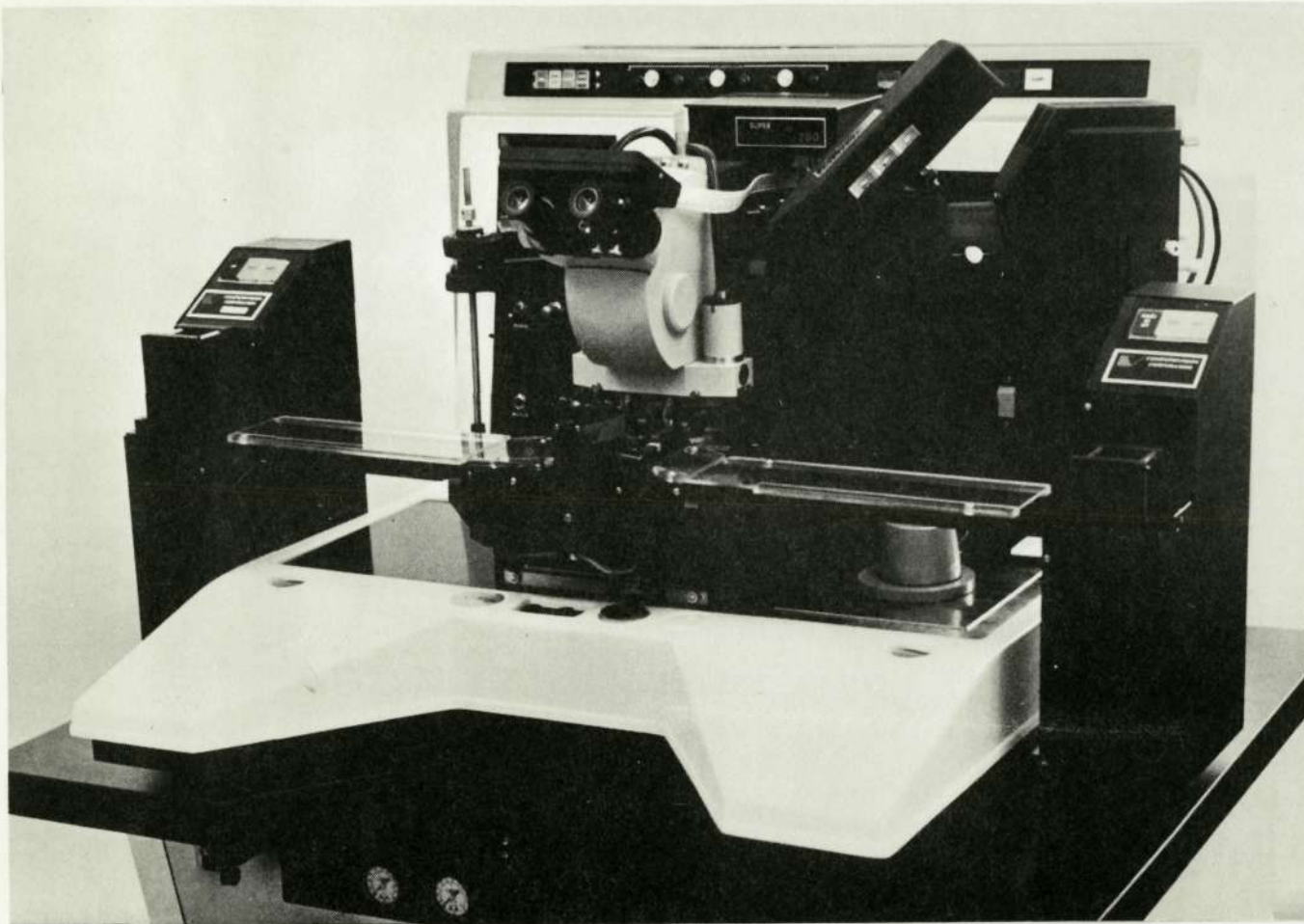
Figure 3-1. Fully Automatic Mask Align and Expose by <u>Computervision Corp.</u> with <u>IMS</u> Wafer Handling System

Figure 3-2. Automatic Spin Coater (Or Developer)
and Infrared Dryer with Wafer Carrier
System by International Instruments, Inc.

on many systems. The normal diffusion furnace is a batch-type unit. If doped oxides are used as a source, an automatic CVD system (Appendix B) is used for oxide deposition, and a batch furnace for drive-in. A proposal for a continuous system for boron diffusion has been proposed by IMS using BBr_3 or boron nitride as the source material. This equipment (see Appendix C) could be used for many types of diffusions by loading boats of wafers in a stand-up position onto the quartz pallets shown in the sketch for individual wafers. The uniformity should improve greatly with continuous diffusion furnaces and thus permit greater automation of the subsequent photoengraving and diffusion steps. However, batch methods with automatic insertion and withdrawal are simpler and comparable in performance (see Appendix D).

3.1.3   Chemical Vapor Deposition

Motorola has been devoting effort to the automation of deposition systems (such as epitaxial silicon reactors) for many years. Contract No. F33615-68-C-1483 with the Air Force Materials Laboratory explored the automatic control of epitaxial systems using analog methods (see Appendix B). Commercial equipment manufacturers such as Applied Materials Technology and Tylan have developed components for automatic composition and flow control of CVD systems. CVD reactors may be used for epitaxy, glass passivation, deposition of doped oxides as diffusion sources, or deposition of polycrystalline silicon and nitride for the silicon-gate CMOS process.

3.1.4   Vacuum Metallization, Plating and Machining

Automatic control of the process parameters for evaporation, sputtering, plating, lapping, grinding, etching and die handling is possible but full automation of this segment of the line will be difficult. An incremental approach is desirable which will allow the facilities to be adaptive as yield and process information is fed back.

Plating equipment was studied for automation, but the
question of handling wafers from the batch carriers to the plating
fixtures has not been resolved. A similar handling problem exists
in the loading of lapping plates and vacuum fixtures. The full
automation of these operations will require development of dump-
transfer or mechanical handling equipment.

Mechanization of these operations has progressed to
the point where high volume production at moderate cost is now
routine, but the "operatorless" systems have been unsuccessful
to date.

3.1.5   Cleaning

The surface preparations prior to various basic operations
are sometimes centralized for better utilization of chemicals,
storage and treatment facilities, etc. The processes are usually
batch operations and thus mechanization has centered around
handling of the carriers, control of temperature and composition
of the chemicals, agitation, rinsing to specific resistivity of
water, and fast drying. Fluoroware, and Fluorcarbon have produced
spin rinser/dryers which illustrate one method of mechanization.
The Millipore Company has developed rinsing stations which control
the rinsing process and conserve water. The work is just beginn-
ing in this area, and automatic batch-processors should appear
in the next year for acid cleaning, rinsing and drying. For
this report, several cleaning methods were studied and temperature
of the acid was found to be a key variable when selecting carrier
materials (see Appendix E).

3.2   BATCH PROCESSES

Thus, the individual wafer processes used in most
photoresist steps, and the batch processes common for diffusion
and wet chemical processes are easily mechanized by obtaining

equipment which handles the wafers in and out of the operation and controls the process parameters. Early forms of mechanization included transfer systems which moved baskets of wafers from one bath to another for cleaning, etching or stripping. The process was controlled by timers and various agitation schemes while composition control of the solutions was maintained by dumping and remixing after a certain number of baskets.

The relative success and low cost of batch processing suggests that in-line systems would be difficult to justify unless the yield improvement was substantial. For planning purposes, it will be assumed that these will remain batch operations, but that in-line systems (such as the IMS diffusion schemes described in Appendix C) will be available for evaluation in the future. The yield tests to justify this type of equipment would require six months or more of set-up, testing and running with hundreds of wafers. Some large companies have already done this, but reports are vague and most small groups could not see the difference.

3.3   WAFER HANDLING SCHEMES

The choice of a carrier system for the wafers during transfer and processing is of major concern. Since many of the operations are batch processes, the industry has developed various boats which hold 10 to 100 wafers. A "standard" seems to be evolving in the form of a dump-transfer boat which holds 25 wafers and mates to similar boats made of various materials for storage, etching, rinsing, feeding of machines, etc. The IMS carriers shown in Figure 3-3 are typical of this design. Several manufacturers make compatible carriers. The spacing between wafers has been widely debated, but 3/16 inch is becoming a "standard".
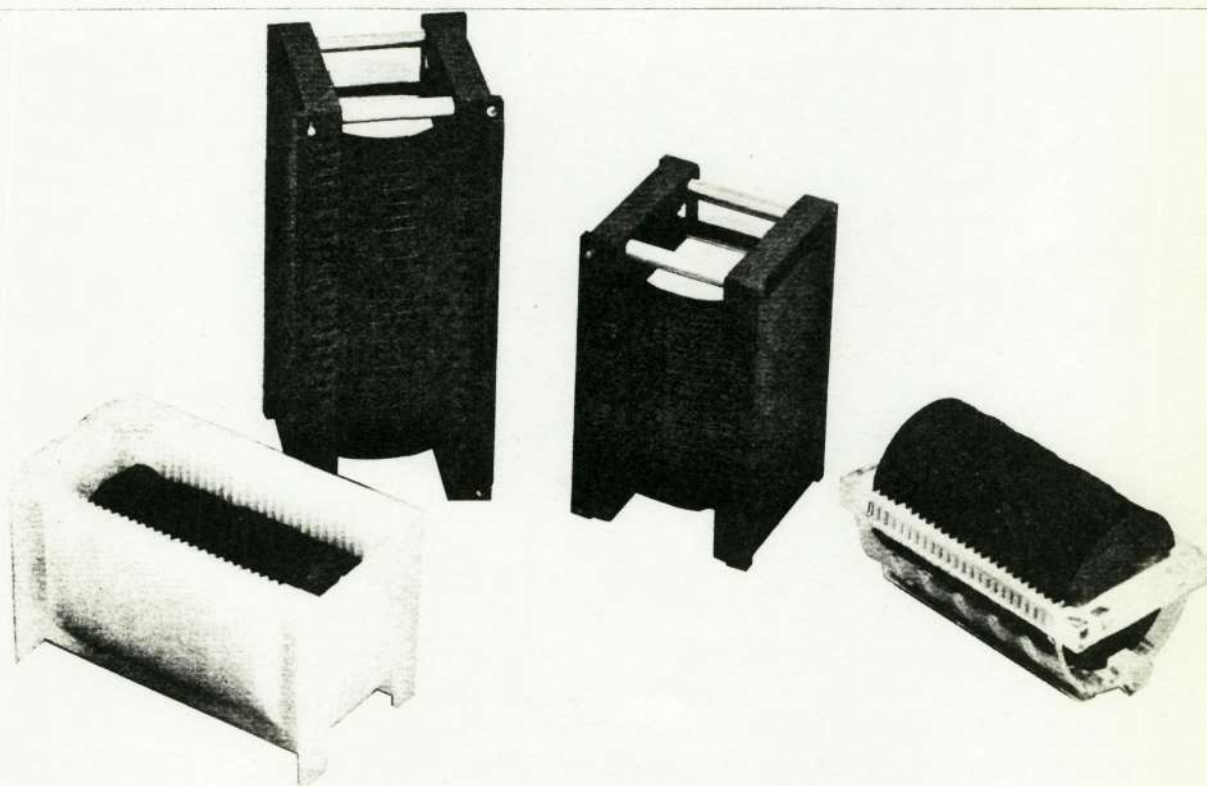
Figure 3-3. IMS Carriers

3-8

The wafer carriers themselves may be carried in another box with a dust cover and a holder for the lot control cards and routing instructions. Data cards which program the processing equipment can be attached to the box, and data read out of the processes can be sent on with the lot so that data is available for checking the centralized data collection system and for lot failure analysis. It is possible to transfer the boxes or the wafer carriers on belts or air-bearings from one operation to the next. A side trip through an evaluation and production control facility can thus be automatic so that 100-percent lot checking is assured. This type of transfer equipment makes the line less flexible in some respects, but control and labor savings are important considerations.

An alternate carrier which has become popular is the four-or-5-wafer tray used by International Instruments for handling and storing wafers (see Figure 3-4). The equipment designed around this tray is shown in section 3.1.1, Figure 3-2.

The flat wafer tray may permit easy inspection and handling through the photoresist operations, but the batch operations require another approach such as the IMS carrier or the standard Fluoroware "wheel" boats. Handling from one type to another is a problem, and it is the writers opinion that the IMS approach is optimum. A great deal of equipment will be available soon which is designed to take this type of carrier. Since 3-inch wafers are becoming popular, and the carriers become $3\frac{1}{2}$ x 4 x 6 inches, it is important to consider this in designing batch processing tanks, dryers and other equipment. A 50-wafer lot (two carriers) is a common lot size.

During dump transfer from one boat to another, the wafer must be lowered into the slots gently (dumping fixtures which permit smooth transfer with no chipping are simple to make). For control
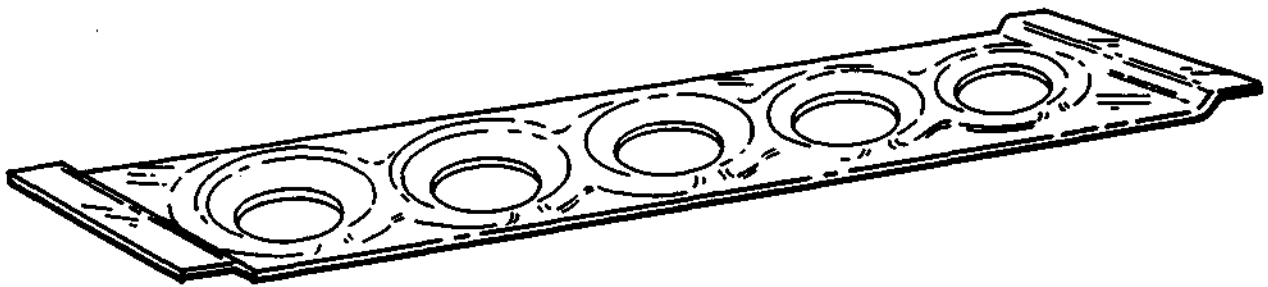
Figure 3-4.   International Instruments Carrier

of contaminants, it is important to always use the same boats at each station; that is, special boats for J-100 stripping, others for acid cleaning, clean boats for rinsing and diffusion, etc. The common storage and transfer boats should be cleaned periodically.

The actual wafer handling in machines designed to process one wafer at a time is usually accomplished by vacuum chucks or air bearings. The IMS system is described in Appendix C. The handling in and out of special fixtures (such as plating, metallizing, lapping, etc.) is presently performed manually; however, better methods should be developed. No improved techniques were found in the course of this study, although several companies are studying the problem. Possibly the operation at the end of the beam-lead sequence will require a special flat carrier or customized load/unload mechanisms for each fixture.

3.4   MAJOR EQUIPMENT

During the report period, operating tests were performed on some of the major equipment which is available for "instant automation." The process capability and ease of maintenance were major considerations. Ability to program and read out process variables was investigated, as was the compatibility of the equipment for an overall system.

Production rate claimed by the manufacturers was verified and down-time was estimated from the limited amount of operating experience possible. A large amount of field data is available informally, but no company would provide actual rate and down-time data for obvious reasons.

3.4.1   Equipment Available, Costs, Problems

Table I presents summary information on the equipment which was studied at Motorola and in field trips. This list is

TABLE I
SUMMARY OF EQUIPMENT INFORMATION

OPERATION	MANUFACTURER & EQUIPMENT	REMARKS
Photoresist Coating	IMS Spin Coater, 4 head, Approx. $20,000, 500/hr. Will wash & dry, coat.	Handles wafers on air bearings from cassette to cassette. Latest model programmable.
Photoresist	International Instruments 4 head, 450/hr., approx. $12,000. Will wash & dry, coat. 5 head for 2" also available. Fully automatic handler & IR bake system with coater for $25,000.	Handles wafers on trays, complete system moves tray through coater and IR bake oven.
Photoresist	Plat-General, 1 head, approx. $7,000, est. 120/hr. Wash & dry, coat. (See Figure 3-5)	Handles wafers with vac. transfer system from cassette to cassette, available soon.
Photoresist	Zicon Spray Coater Epec Spray Coater In-Line Systems Spray Coater (See Figure 3-6)	Alternate method of coating, three suppliers with equipment for thick coatings, possibly for general use, not tested in this program. No wafer handling supplied.

NOTE: Many other coaters are available, but the wafer handling requirements eliminate most of them. The sprayers are included because they may improve yields if handling systems are added (reported lower pinhole counts, but not tested for thin PR films in this study).

Photoresist Developer	The spin coaters above can be modified for spray develop. All companies supply a developer for price similar to coater.	See above for handling.
Photoresist Developer	Batch developers usually built by circuit manufacturers, low cost tank-type.	Cassette batch, dip.
Align Mask	Computervision Autolign $40,000 approx. >150/hr. One operator per 2 or 3 machines possible.	Handles wafers with IMS air bearing from cassette to cassette, 1-micron error, fully automatic.

TABLE I (Cont'd)

OPERATION	MANUFACTURER & EQUIPMENT	REMARKS
Align Mask & Expose	Cobilt Aligner, approx. $10,000. Handling is about $7000 extra.	Manual Aligner, 50 to 100/hr. With IMS-type handling, cassette to cassette, optional. May supply tray handling as option soon.
Align Mask & Expose	K & S Aligner Kasper Aligner	Manual systems, competitive with above, but not tested for this program. Plan to offer cassette handlers, possibly trays also.
Align Mask & Expose	International Instruments Mask alignment system est. $28,000, 100-150/hr.	Tray handling & TV viewing, manual alignment, will be available soon.
Align Mask & Expose	Projection Printing Probably will mature in 1972-73 period. $40,000, 50/hr.	Resolution has been poor for CMOS work, and wave-length not suited to negative resists on some machines.
Inspection	Cobilt, IMS Estimate $4000 plus microscope	Equipment being built to handle wafers from cassettes, available by Jan. 72.
Inspection	International Instruments Color TV system	Planned for 1972, cost unknown, handles trays.
Nitride Deposition	AMT Nitrox with automatic flow controllers. Approx. $40,000.	Radiant heat, no wafer handling capability. (30 wafers capacity).
Nitride Deposition	Any diffusion furnace, plus special tooling for automatic gas control and gas preheat, approx. $15,000	Estimate 20-30 wafers per run, uniformity may be a problem, very high gas flow rates.
Silane-type Oxide deposit	AMT, MRC, Thermco, Hugle, Ion Equipment, et al. $5000 to $25,000	Semi-automatic common, fully automatic now available but without wafer handling.
Metallization	Platinum, titanium, and gold can be sputtered in many semi-automatic systems. At least 10 suppliers.	No wafer handling, but most processing is automated.
Circuit Separation	No good method found yet.	This a major problem area for automation.

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TABLE I (Cont'd)

OPERATION	MANUFACTURER & EQUIPMENT	REMARKS
Diffusion	HLS Gas control & boat load/unload, about $5000/tube plus valves and jungleware. See Figure 3-7	New, quartz screw system. Gas control card programming, 1 tube at a time.
Diffusion	Thermco linear boat puller about $1500/ tube. Program board for gas sequencing also available.	Low cost puller, protrudes from tube.
Diffusion	Bruce Industrial Controls (Appendix D) Automated batch diffusion.	Automated diffusion systems. Major installation @ Western Electric in Reading, Pa.
Cleaning	Millipore (See Appendix E) Fluorocarbon, Inc. Fluoroware, Inc.	Many suppliers.
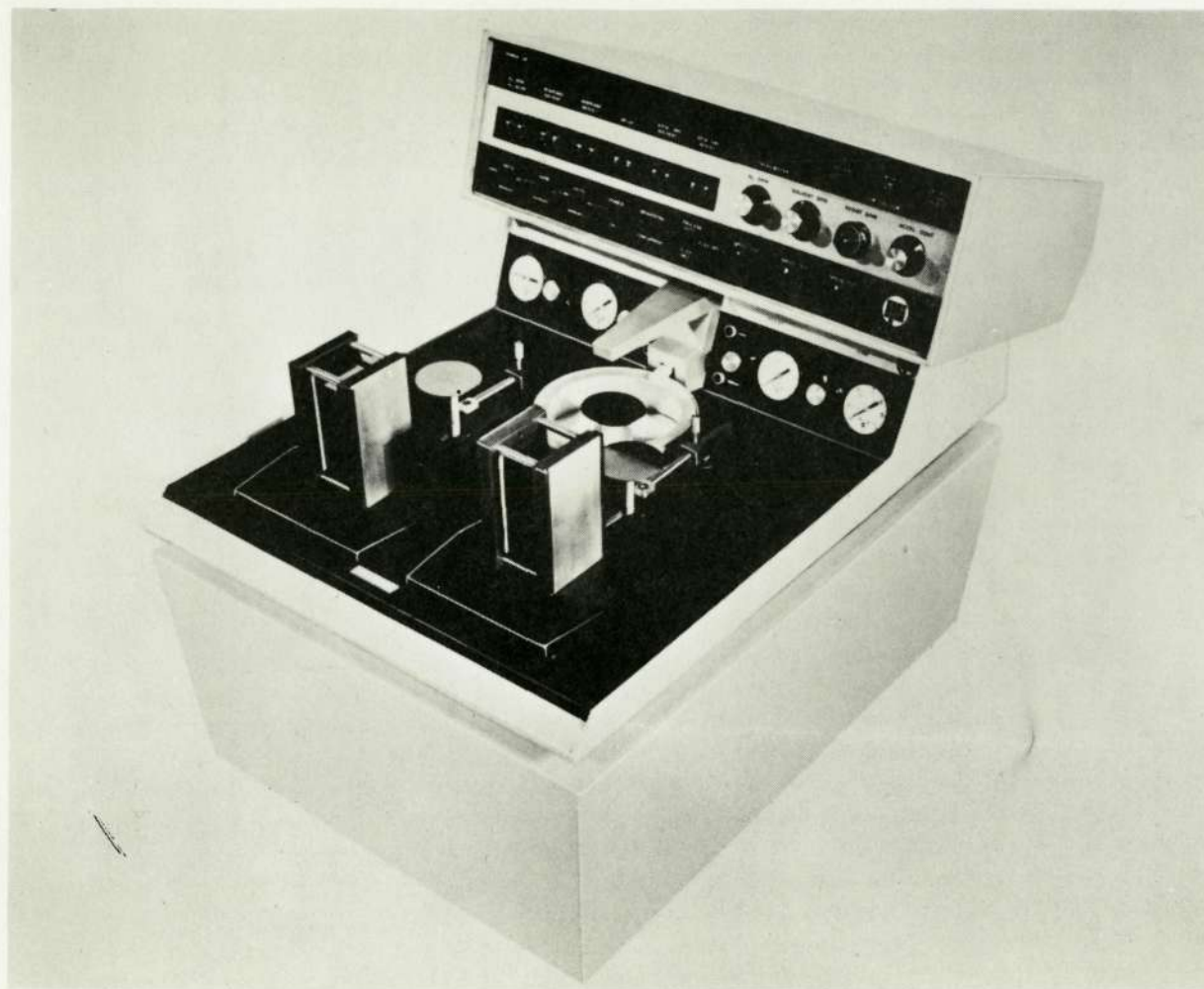
Figure 3-5.   Plat-General Automatic
Coater/Developer

Diagrammatic cut-away
of Model 1400
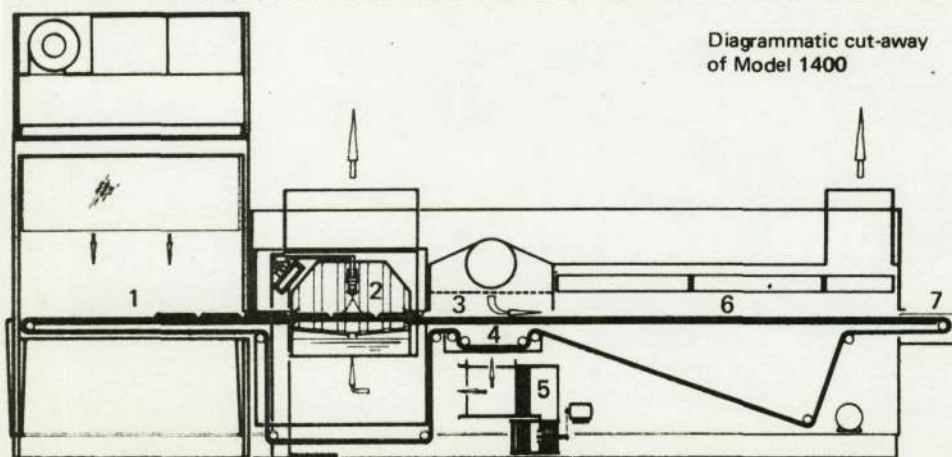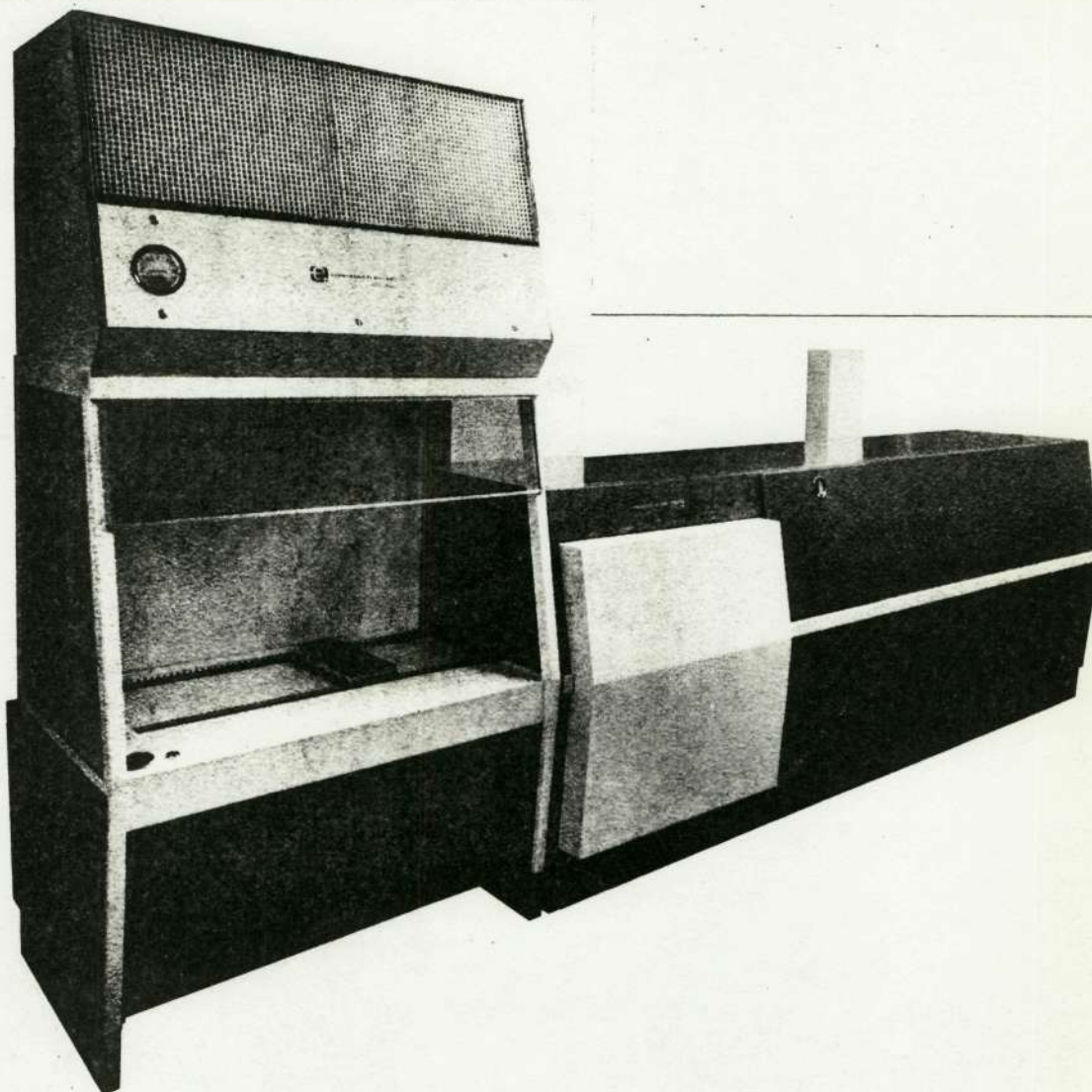
FUNCTIONS

1. Loading Station
2. Spray Chamber
3. Air dry Section
4. Chain Cleaner
5. Filter Blower Unit
6. Infra Red Drying Oven
7. Unload Station

Figure 3-6.   EPEC Industries, Inc. Model 1400 Precision
Spray Coater and Infra Red Dry System

Figure 3-7

HLS AUTOMATIC CARD READER
SEQUENTIAL TIMER SYSTEM

Model No. 118-110

1. <u>Input.</u> Standard punched card with following instructions:

   -- 4-digit job number.
   -- Total process time in minutes.
   -- Up to 4 individual time intervals (in minutes or seconds)
      with any 4 of 9 functions per interval.
   -- For use with HLS Model No. 150-400 Boat Puller including
      4 rates and 2 delayed stops (enables boat to be stopped,
      movement delayed and then re-commenced at different rate
      if desired).

2. <u>Method of Operation.</u>

   -- Pre-punch standard card with process data.
   -- Insert card in Card Reader.
   -- Press "LOAD DATA" and withdraw card.
   -- All data is now loaded into memory.
   -- For process verification, press "DATA VERIFY".
   -- To commence automated process, press "RUN".

3. <u>Circuitry.</u> Digital Solid State for maximum control, reliability,
   precision, and elimination of setting errors.

4. <u>Signals.</u> Visible light indicates program is in progress.
   Flashing light and audible signal indicate end of process.

5. <u>Resolution.</u> .01% of full scale.
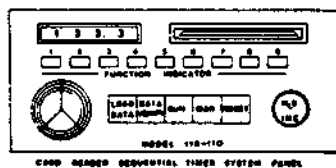
6. <u>Accuracy.</u> .01 seconds.

2576 Lafayette Street, Santa Clara, Ca. 95050. (408) 296-7436.

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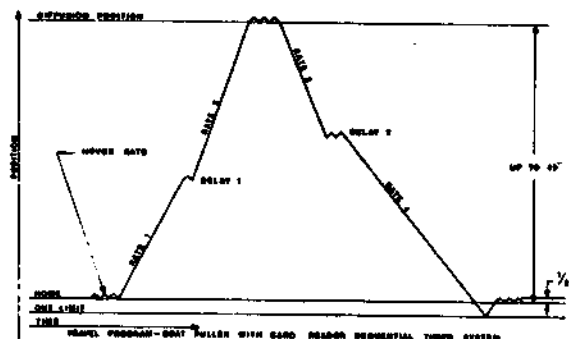
Figure 3-7 (Cont'd)

FEATURES OF THE HLS AUTOMATIC BOAT PULLER.

1. <u>Boat Travel.</u> Digitally adjustable from 1 to 49 inches.

2. <u>Boat Rate of Travel.</u> Digitally adjustable in two ranges:-

   Range 1 - .1 to 4.9 ins/minute.

   Range 2 - 1.0 to 49 ins/minute.

3. <u>Boat Direction and Rate Control.</u> With HLS Model No. 118-110 Card Reader Timer, the Boat can be programmed to stop, delay movement for a short time and then re-commence movement in the same direction at a different speed if so desired.

4. <u>Boat Hover Mode.</u> $+\frac{1}{2}$, -0 inches, oscillating to prevent seizing of Boat to tube.

5. <u>Boat Weight.</u> Maximum, 4 pounds (loaded).

6. <u>Boat Position and Direction.</u> Indicated at all times by LED display.

7. <u>Boat Over-Travel.</u> Eliminated by internal limit switches which also reset electronic controls.

8. <u>Method Of Operation.</u> A DC, bi-directional Stepping Motor driven by special phase-locked loop circuitry provides motion through a flexible shaft to a quartz helix. Lateral movement is provided with a quartz follower on the helix to which the wafer boat is easily attached. The helix is driven from one end of the furnace tube and the wafer boat loaded to the helix at the opposite end.

9. <u>Automatic Operation.</u> Compatability with HLS Model No. 118-110 Card Reader and HLS Model No. 115-300 Sequential Timer System provides complete automation of processing.

10. <u>Circuitry.</u> Digital, Solid State for maximum control, reliability, precision, and reduction of setting errors.

11. <u>Materials.</u> All quartz materials including helix, helix followers, and furnace tubes are of high purity quartz. No other materials enter the furnace tubes.

12. <u>Power.</u> 115 VAC, 60 Hz.
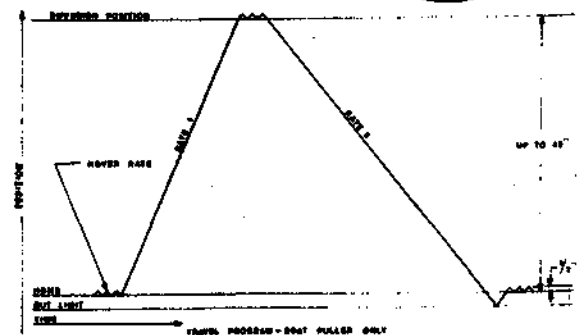
INCORPORATING SOLID STATE DESIGN FOR INCREASED CONTROL
AND RELIABILITY.

NOT a recommendation, but results merely from the time limits of this report period and the relative cooperation of the various suppliers. It is important to note that there are several sources for most items, and there is much equipment which is available "off-the-shelf" for prompt implementation of major portions of the automation plan. The key factor is the selection of the method of wafer handling. The two most popular methods, trays and cassettes, were illustrated previously. Many companies contacted indicated plans to provide their equipment with both tray and cassette loading capability. During the next few years this trend should continue until a complete line is available utilizing either approach.

3.4.2   Equipment to be Developed

Additional equipment not yet available to complete an automated line is listed in Table II. The list is not complete and many items may be found on the market which this writer did not locate in the time allotted, but distribution of this report may resolve this problem.

3.5   DATA PROCESSING

A survey of process and product specialists was made to determine the specific information which should be read into and out of a process step in order to control the process and provide data for improving product performance and yield. This list is not complete, and would certainly be updated continuously as more knowledge is acquired in the operation of the line.

3.5.1   Information For Process Control

The precise control of time, temperature, pressure, acceleration, velocity, flow rate, composition and other variables

TABLE II

SUMMARY OF ADDITIONAL EQUIPMENT REQUIRED

OPERATION	EQUIPMENT NEEDED	REMARKS
General	Control Computer and interfaces for major equipment	Many sources, will require six months to implement and special interface items must be designed and built.
Photoresist	Tray handling for alignment tools	New tool being built by International Instruments. Other tool makers are now beginning to offer tray handlers for their standard aligners.
Batch etch & strip, wafer cleaning	Transfer systems for tank to tank movement of cassettes	Most built in-house by circuit manufacturers. Few have controls.
Metallization, CVD, plating lapping.	Wafer handling in and out	Will require in-house efforts due to variety of workholder designs.
Circuit Separation	Tooling for etch & separate	In-house effort required.

is basic. Derived parameters such as resultant thickness, etch rates, or conductivity are not usually directly controllable at this time, although much progress has been made and will be made in the next few years. Many things can now be measured during the process that used to be measured after the fact.

One control strategy that has been suggested is the "measure everything" approach, which does not suggest controlling everything until many iterations show the significance of the variable by statistical techniques. Digital computers are well suited to this type of data collection, storage and analysis. Direct computer control eliminates operator "body English" and still allows "tweaking" of the process. This information storage and analysis is considered to be a primary goal of the automation scheme, since yield improvement is the dominant cost reduction which can be made by mechanization.

3.5.2 Information for Product Control

Inventory control, shop order tracking, routing and scheduling can easily be computer-controlled so that the right product arrives at the right place at the right time. Once process control is achieved and the product attributes are measured, complete specification is possible, and the overall quality and reliability of the product is upgraded. Long-range product control entails the ability to reproduce to the more stringent specifications at any time. The large number of products which are produced in any given wafer fabrication line requires the complete specification of the product made possible by tight control and information storage. Product engineers must obtain dependable electrical parameter distributions for specifications or redesign of the product.

3.5.3 Yield Improvement By Data Analysis

Statistical techniques such as multiple correlation analysis, trend analysis or even complete computer simulation of the processing line should provide information for yield improvement. The process control computer can provide the data necessary for this type of analysis. Off-line systems can be utilized for the analysis so that the process computer can be quite simple. Time-sharing programs are available from any sources for statistical analysis. Simulation models must be developed and tested carefully, but can then be run on systems available to most small shops. Major manufacturers generally have large computer systems in-house for simulations.

A general discussion of process control by computer follows to illustrate the basic concepts.

3.5.4 Process Control By Computer

For more than ten years computers have been used in the area of process control. The type of computer used for this application has been given the imaginative name Digital Process Computer. The Digital Process Computer differs from the Data Processing Computer and Scientific Computer in system size and computing power.

The Data Processing Computer, typically the largest in system size, requires extensive data storage capability. This storage capability is in the form of magnetic tape units, which are also used as high speed input/output media, and magnetic disks or drums, which are used to store data and programs used frequently by the computer. This large storage capability is used to amass the voluminous data necessary for the various reports which are spewed from the high speed line printers and distributed to system

users. The magnetic core requirement of this type computer is relatively small. Input/output driver programs and search/sort programs are usually the only programs required to be core resident. Since Data Processing computers operate primarily in a non-real-time environment, speed is typically slower than the faster Digital Process Computer. Indeed, speed is sacrificed for power in handling batch oriented input/output tasks.

The Scientific Computer is very similar to the Data Processing Computer except for two major areas. First, it does not require the extensive data storage capability. Second, it requires a large amount of magnetic core storage. The more important difference between these two systems is the magnetic core storage requirement. The Scientific Computer typically performs extremely complex mathematical calculations on small amounts of data. Therefore, the emphasis is on the capability to store the necessary programs to perform these calculations. As in the Data Processing Computer, speed is of secondary importance and is sacrificed for computing power. It should be obvious to the reader that the Data Processing Computer, configured with large amounts of magnetic core storage, will double as a Scientific Computer.

The Digital Process Computer, typically the smallest in system size, is usually a medium sized or mini-computer. The price for a system varies with the associated process complexity, but is usually less than $100,000.00, whereas, the large Data Processing and Scientific Computers are in the multi-million dollar price range. The Digital Process Computer is designed primarily to operate in a real-time environment. It must be there, ready to act or react instantaneously to any process anomaly. Therefore, the emphasis is placed on high speed input/output circuits. The magnetic core memory is also high speed in nature

in order to allow fast tests on process parameters to facilitate any necessary adjustments in control elements. Data storage requirements are far less than other systems and are usually accomplished by magnetic tape units and/or magnetic disks. Systems using magnetic tape units also have the capability to use these tapes as input/output media for a Data Processing or Scientific Computer. Tapes can be carried to another system with compatible data formats for further processing. The Digital Process Computer is becoming a powerful tool in many industrial applications.

Process control by computer can be accomplished in several ways. However, two methods are used most frequently and will be discussed. These two methods can be combined in varying degrees to create systems which vary in complexity from very simple to extremely complex.

Computerized Process Monitoring is a method of process control used by the more conservative system users who fear putting all their eggs in the computer's basket. In this approach, the computer simply acts as a monitor for manual programmed process control units. It gathers data for future study and flags any system errors during the process cycle. The data gathered by the computer can be used to modify the manual settings on subsequent process runs and to generate various performance reports as required. With the system, any failures in the computer or its peripheral devices will not affect the ability to continue the process.

The most progressive, perhaps the state-of-the-art, method of process control is Process Control by Computer with Adaptive Feedback. With this method, the computer is the master of every operation in the process. Various process parameters and limits are presented to the computer by the operator through an input/output device. After the completion of the initialization

dialogue, the computer takes over. It reads all pertinent data during the process and, with the principle of adaptive feedback, adjusts critical process settings in order to optimize final results. The obvious return with this approach is the ability to attain the same results repeatedly even with major changes in the ambient environment. Fluctuations in line voltage, room temperature and humidity, etc., can be tolerated by simply adjusting other process parameters such as time and temperature. Serious process anomalies can be corrected with the help of debugging aids which are pre-programmed in the computer. Thus, system down-time can be reduced to an acceptable level. More data is available to system users with this approach than in the conservative approach described above. Each adjustment made in the process can be printed for further investigation in addition to the required performance reports.

Virtually any piece of electronic, electro-mechanical, or electro-chemical equipment can be interfaced to a computer. Examples of this type of equipment are as follows:

(1) Digital to analog converters

(2) Analog to digital converters

(3) Digital voltmeters

(4) Frequency meters

(5) Counters

(6) Real time clocks

(7) Mass flow meters

(8) Temperature sensors

(9) Position indicators

(10) Stepping valves and motors

Typically, equipment of this type is used to measure or control some process parameter such as gas flow, temperature, voltage, current, pressure, etc. The readout and programming data format can be of several types such as weighted binary, offset binary, or binary-coded-decimal.

Other pieces of peripheral equipment primarily used as data input/output devices are available in all sizes and shapes. Some examples of this type of equipment are as follows:

(1) Card readers and card punches

(2) Mark sense document readers

(3) Paper tape readers and punches

(4) Page printers

(5) High speed line printers

(6) Keyboards

(7) Disk memory devices

(8) Drum memory devices

(9) Magnetic tape units

(10) Cassette tape units

In conclusion, the advent of the mini-computer and the availability of peripheral equipment coupled with the increasing sophistication of the higher level programming languages, has brought computerized process control within easy reach of many firms. In addition, the repeatability and predictability of processes has made computerized process control an enviable asset.

3.6   EFFECT OF AUTOMATION

A simulation model was used in this study to analyze machine rates, labor rates, yields and floor space requirements

given the usual assumptions. The true value of the model is in the analysis of cost sensitivity by operation given optimistic, pessimistic and likely values for rates and yields. The intangibles dominate in many cases, and that is the reason most wafer processing facilities are not automated. It is difficult to show real cost savings without speculating on yield and reliability improvements. Since yield and reliability are always increasing for any given product (during the growth period, which is the entire life cycle for many products) management discourages automation, believing that things are improving without it. A major benefit of automation could be the data correlation which might increase yields on new products. System flexibility must be adequate to absorb new products and new processes quickly.

3.6.1   Labor and Overhead

The complete elimination of all direct labor would not reduce the cost of most IC wafers by more than 30 percent since materials cost and overhead are important factors. Automation would save 10 to 20 percent in finished wafer cost if yield did not change. This same amount could be saved by increasing wafer size and lot size, if yield would remain constant.

3.6.2   Yield Improvements

The yield on beam-lead CMOS circuits of LSI complexity is quite low, possibly 1 to 10 percent. In some plants, half of the wafers never reach electrical probe test. This 50 percent could benefit from automation by the elimination of wafer breakage and processing mistakes. The other yield losses are associated with mask defects (correctable by newer mask-making methods, but too expensive until projection printing or an equivalent method is perfected) and random defects in the material caused by handling,

thermal cycling, etc. Some improvements can be expected from programmed furnace insertion and withdrawal rates, wafer handling systems, and data analysis for mask problems or process capability changes. The overall yield improvements could lower circuit cost by a factor of 10. Normal yield improvements of that magnitude generally require years and are never realized for some products. With automated processing and data analysis, this improvement might be achieved in a few months for a given product after the line has been running for a year. This could save 1 to 5 million dollars a year in a high volume line producing LSI circuits.

3.6.3 Reliability Improvements

A fringe benefit of high yield is better product reliability, since lot qualification tests could be of great benefit with really homogeneous lots and acceptance levels could be tightened economically. A general improvement can be expected from the elimination of tweezer handling and operator "English". It is difficult to assess the cost savings to the circuit supplier, but fewer returns and lower engineering costs should result from better quality circuits. The value to the end user is obvious.

SECTION IV

4.0   OVERALL PLAN FOR AN AUTOMATED CMOS BEAM-LEAD LINE

Any plan will depend on the volume requirements of the
line, but a reasonable assumption might be 100 wafers per hour
through any process step, thus 800 to 900 per hour through the
photoresist steps, given 8 or 9 masks. This is a typical pro-
duction run rate, providing approximately 10,000 wafers per week
on a three-shift basis. A small pilot operation or captive line
producing a few circuit types would probably require one-tenth
this capacity. Most automatic equipment is designed for high
volume, so the line should be designed to produce a broad range
of products, perhaps CMOS, N and P channel circuits, MOS discrete
devices, and perhaps also bipolar circuits with multilayer
metallization. The cost of automating a laboratory operation is
not much less than a production line.

The minimum volume line (highly unbalanced) will require
one alignment tool such as the Computervision machine and will
thus be limited to approximately 150 per hour divided by 9 masks
or about 16 wafers per hour at all other operations. This would
provide approximately 1000 per week on two shifts.

Photoresist steps can match the 150 per hour rate of
the aligner so that an overall rate from coat to etch will be
attained with equipment costing approximately $75,000 plus data
interfacing. The diffusion facilities will cost approximately
$100,000; batch cleaning facilities if centralized can be set up
for $25,000; and metallization will be approximately $50,000.
Minor equipment and hoods add another $50,000. Data interfacing
and a supervisory computer with memory could cost from $30,000 to
$300,000 depending on the specific requirement. A $30,000 epitaxy
system will provide all CVD process capability in the short run.

After initial experience with the processing in the pilot line, a rigorous analysis of the data gathered by the supervisory computer system is essential. The operating volume of the line is then selected and the troublesome equipment replaced. A reasonably balanced line using modular units will allow gradual expansion of the scale of operations until the desired run rate is reached and the process is baselined. The evolutionary development of such a line will probably require three years and could cost from $1 million to $5 million depending on the degree of handling and process control automation, the run rate, and the size of off-line analytical facilities. An achievable goal of 10,000 wafers per week (delivered to electrical test) will probably require one year for process and equipment debugging, one year to build from 1000 to 10,000 per week, plus the first year of planning and facilitizing, and will cost $2.5 million minimum.

Photoresist - 100/hr x 9 masks = 900/hr.

2 Spinners with dryers	$ 50,000
2 Developers with baking	50,000
8 Automatic aligners	320,000
8 Inspection stations (pattern)	35,000
2 Batch etchers	20,000
2 Batch strippers	20,000
4 Inspection stations (etch)	15,000
	$510,000

Diffusion - 100/hr per step

12 Furnace tubes with pullers and Controls	$200,000

Chemical vapor deposition, 100/hr per step

1 Nitride and poly deposition system	$50,000
2 Oxide deposition systems	60,000
2 Epitaxial systems	60,000
	$170,000

Centrallized cleaning, 100/hr per step

2 Automatic cleaning systems	$50,000

Metallizing, 100/hr per step

1 Platinum sputtering system	$35,000
1 Titanium-platinum system	40,000
1 Plating module	15,000
	$90,000

Lapping, 100/hr per step

2 Lapping machine	10,000
2 Mounting and de-mounting station	10,000
	$20,000

Evaluation equipment for all above

2 Profile-type thickness gages	$14,000
2 Resistivity stations	4,000
2 Sectioning stations	8,000
2 C-V plotters, complete	20,000
1 Interferometer	8,000
4 QC visual inspection stations	16,000
	$70,000

Optional evaluation equipment

(Major equipment such as SEM, and other analytical
tools are not part of this plan, but must be considered
in any major installation. Cost could run several
hundred thousand dollars.)

Total Process Equipment $1,110,000

Supervisory-mode computers (5)   125,000
Interfacing   25,000
                                                    ──────────
        Total on-line $150,000

Off-line timesharing services - unspecified

Installation costs for all above, estimate $300,000

Clean room costs @ $100/square foot, $1,000,000

Total estimated costs $2,560,000

Additional costs for direct control - unspecified, but
conservative estimates of $300,000 received from reliable
sources. Direct digital control with adaptive feed-
back was eliminated as an alternative because of
amount of in-house effort required. However, some
facilities exist. An analog system for epitaxy is
shown in Appendix B to illustrate typical automation
process for one process step.

4.1   IMPLEMENTATION

The implementation of the automation plan might proceed as follows:

Phase I. Pilot line based on today's processes, paced by the photoresist operation.

Capacity - 1000 wafers per week on two shifts.

Cost - $330,000 capital equipment including a supervisory computer system of the simplest type. Laminar flow hoods would be used for this line to avoid the cost and time of equipping a major clean room. This line should be operational for at least six months before beginning to scale-up for production.

Pilot line studies - During the pilot line operating phase, studies of key process variables and parameters should be made with emphasis on the control capability of various devices such as mass-flow, temperature, pressure and composition controllers. The effects of thermal cycles on the single crystal silicon wafers can be studied by X-ray topography so that optimum furnace insertion and withdrawal rates, and optimum carrier design, can be determined. Cleaning effectiveness can be observed with radioactive tracer techniques and C-V plot analysis. These types of analysis should be supplemented by statistical analysis of device parameters and yields as a function of process variables. The marriage of analytic and statistical methods should allow fast problem solving, so the production phase can be started.

Phase II. Decisions must be made on expected yields, throughputs, downtime, critical variables, major equipment, special facilities, wafer and carrier handling systems, special

training programs, off-line support, type of contamination control needed, and physical layout.

The major expenditures required for the production phase will concern several levels of management. Successful pilot results and hard data on the effects of automation on yields will aid in obtaining management approval. Keeping in mind the alternatives of bigger batches, bigger wafers, and simpler circuits or automation, the costs are placed in proper perspective. Conversion of a raw materials facility from 2-inch to 4-inch wafers (crystal growth, slicing, polishing and evaluation) could exceed the cost of automating a 2-inch wafer fabrication line by a factor of 2 or 3. Costs for mask manufacturing for larger sizes is not simply the scaled-up cost of materials. Flat glass is not available with normal photographic emulsions used in mask-making, and the run-out in image stacking is too great to permit small geometry devices to be made on very large wafers. Newer methods of mask making, such as step-and-repeat on resist-coated chrome, may be necessary in order to utilize larger wafers. Also, the "throw-away cost" of broken pieces and low yield wafers is greater with large wafers, so there is a tendency to compromise the system and run marginal material through to final electrical test. The handling systems generally will not process small pieces, so rework lines are established, and control is further complicated.

If clean rooms are to be used (at a minimum of $100/square foot) they must be flexible enough to allow major changes in equipment and materials flow. Recent studies have shown that the small size and lower headcount possible in an automated line reduces contamination considerably.

The smooth transition from pilot to production levels of operation is complicated by consideration of clean rooms. A 6-foot x 3-foot laminar flow hood costing $1500 could be utilized at one-half the cost of a clean room when the 3-foot space in front is added. However, there is evidence that laminar flow hoods do not solve the contamination control problem with certain types of equipment. Obviously, a special study of newer clean room concepts is needed before the production phase of this program could begin.

Assuming the Phase II decisions are made, and management has approved the overall concept, a gradual build-up from 1000 wafers per week to the selected level of production can be accomplished by the addition of specialized CVD and photoengraving equipment, and the duplication of diffusion, cleaning, metallizing and lapping equipment. For example, an epitaxial reactor can be used for single crystal, polycrystalline silicon, nitride and oxide depositions during the pilot phase by changing boats and tubes. As volume increases, specialized systems are needed. If funds are available, this special equipment should be purchased and debugged before Phase II (at a cost of $110,000). Small CVD systems for epitaxy and nitride deposition are not much less expensive than production systems, especially if they are computer monitored. Alignment tools and inspection stations can be added gradually, provided that compatability in processing and wafer handling is assured. (Image runout can occur if different alignment tools are used for each layer, particularly if one tool is a "vacuum" type and another is a "back-pressure" type.)

The concept of a pilot line evolving into a production line, rather than parallel arrangements, takes into account the need for close engineering support and the absence of "surprises" such as might occur when one team of specialists trys to scale up the work of another team. Computer monitoring will allow re-

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construction of any process, and automation will eliminate operator and engineering "English" so experiments can be conducted in the production line without "losing the recipe". Thus, a separate engineering operation is not required. This does not mean that laboratory work on the basic unit operations and processes will be eliminated, but the in-between step of a preproduction pilot line for each new process can be eliminated once this monitored line is established.

Thus, it has not been intended to submit a rigid plan for construction of a $1 million to $5 million line to produce 10,000 beam-lead CMOS wafers per week, but rather to suggest an initial expenditure of less than $500,000 to attain process capability and permit production of significant quantities of wafers. A build-up can then be based on proper equipment and process evaluation, and the changing technology can be accommodated with minimum impact on the facility. The industry has matured sufficiently to allow this type of effort without enormous in-house mechanization programs.

Without automation, pressure for more complex circuits will result in low yields and drifting technology. The number of process steps has increased to the point where automatic control is essential, and in most cases the equipment is now available. Automatic handling and computer supervision are minimum requirements. Eventually, it will be possible to use adaptive feedback as hard data replaces the folklore of semiconductor processing.

APPENDIX A

AUTOMATIC ALIGNMENT

AUTOMATIC MASK ALIGNMENT IN THE MOS/LSI PROCESS

by

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Introduction

In the manufacture of semiconductors, the presently used techniques of optical mask/wafer alignment and contact printing can be a major performance-limiting operation when fine line geometries have to be precisely positioned in integrated circuits and transistors, especially should the alignment be performed through a dark-field mask. The alignment of silicon wafers relies upon the ability of an operator to position a photographic mask directly over a patterned wafer using a split-field microscope system and the X, Y, θ micropositioning controls, thus allowing for the operator's skill, judgement, emotion, eye deficiencies, eye fatigue, etc., to affect the overall wafer alignment rejection rate.

This study of automatic alignment, directly related to MOS/LSI processing, was carried out using the Computervision Autolign 2686 automatic system fitted to the Kulicke and Soffa model 686 mask alignment machine. The basic mask aligner, which is already widely accepted and used in the industry, provides for nitrogen flushing of the resist coated wafer prior to clamping, vacuum clamping to minimize distortions and a collimated mercury short-arc UV exposure system to adequately define most geometry requirements on either negative[1] or positive photoresist processes.

This evaluation of automatic alignment and mask making feasibility shows how high positional alignment accuracy can be obtained independently of the human error, giving increases in both wafer and die yield and showing greater mask usage, although with some additional requirements being placed on the mask makers.

Mask Alignment System Operation

The "Autolign" system, which depends upon a target-pattern recognition Photo-electric system, has fibre-optic bundles attached to the split field Zeiss microscope providing for illumination and signal characterization of the field of view, thus resulting in output voltages for X, Y, and θ displacement until image correlation is achieved. (See Fig. 1.) This is dissimilar from the BAIRreco correlator-controlled system, which employs imaging optics, scanner-detector, processor and correlator with a claimed object displacement detection down to ±0.1 μ ; this system is more fully described in the paper by N. Altman[2].

The Autolign machine requires a pair of alignment target sets, one set being at either side of the photomask, which after the photolithographic process becomes an etched pattern onto the wafer, this pattern being referred to as a type 'B' pattern. The remaining masks in the photomask series contain complementary sets of target patterns, which will be referred to as type 'A' patterns.

Fig. 1. "Autolign 200" automatic alignment system.

Table 1. Types of B targets and their properties.

Pattern Name	DWG #	Important Parameters
"B"	268 sheet 2	Dark field pattern. Light squares 0.0003 x 0.0003 inch separated by 0.0001 inch spaces. Widely used with fine geometry circuitry.
"BN"	268 sheet 4	Photo negative of "B"
"B-.0002"	347	Light field pattern. Light squares 0.0002 x 0.0002 inch separated by 0.0002 dark spaces. Used instead of above where 0.0001 inch line widths cannot be printed reliably (can be reversed to form dark field pattern).
"B-.0003"	348	Light field pattern. Light squares 0.0003 x 0.0003 inch separated by 0.0003 dark spaces. Used instead of above when lack of resolution requires it.
"B-.05"	440	Checkerboard of light and dark squares measuring 0.0005 x 0.0005 inch. To be used on very coarse devices such as power transistors
"A-.001"	343	"A" type pattern. To be used in all places where an A pattern is required.

Alignment of the photomask pattern to the wafer pattern in this machine is accomplished by optical contrasts between the 'A' and 'B' sets of targets, thus obtaining the best alignment fit between the pairs of 'A' and 'B' targets. With this alignment being implemented solely to the alignment targets and not to the circuitry, it is extremely necessary to use the correct targets precisely stepped into the photomask to utilize the maximum capabilities of this automatic alignment system.

The Autolign machine uses the optical contrast created by the etched 'B' pattern in the silicon, epitaxial or silicon dioxide layer, and compares this to the 'A' targets of the following masks that have been restricted to that area viewed in the microscope. Whilst the actual alignment mechanism is considered proprietary, the character of the etched starting 'B' target should be understood[3].

The B targets are a square array of diamond shapes with an alignment cross in the center of the array. The purpose of the diamond shapes is to cause steps in the oxide layer to be generated. When viewed through the microscope, the transition area about the oxide steps (transition regions) appears to be darker than any horizontal areas on the wafer. The reason for the darkening is that the transition regions are not perpendicular to the optical axis, and therefore, light impinging on these regions gets reflected out of the microscope objectives' aperture. The size of the diamonds in the B type patterns and the separation between the diamonds are designed to give maximum optical contrast of the target and the surrounding area. Therefore, the diamonds are made as small as possible, since it is only the perimeter that generates optical contrast, and the ratio of perimeter to area for a diamond shape varies inversly to the size of the diamond. Thus, the best target is that which has the smallest diamonds that are permitted by the process.

From the above, it might be reasoned that if the oxide thickness and the photoresist system employed are such that it does not permit fine geometry diamonds, then the alignment system performance may be affected. This would be the case, except for two facts--1) there is enough reserve in the system to accommodate large changes in contrast ratio, and 2) as the oxide thickness increases, the width of the transition region grows (since the angle of the transition region is constant, rather than its width). Hence, the proper choice of the B type targets will insure good results for all processes.

Table 1 lists the existing types of B targets available and the properties of these targets.

Examine the list and determine the applicable B type target for the process. In choosing the proper B type target, consider these facts:

1. Use the finest target available that will print reliably. Reliable printing is that in which all transitions appear in the oxide.
2. The final shape of the diamonds in the oxide is unimportant. It is common for the diamonds to degenerate into circles. The important criterion to be met is that all the diamonds print and are retained through the etch process.
3. Choose the proper polarity of the B target. For example, in a given masking process, it may be better to cut small holes in the photoresist than to leave small squares of photoresist on the silicon. Therefore, it is important to examine the way in which the wafers are handled (overexposed, properly exposed or underexposed, negative or positive resist), then select the proper polarity of the pattern.

Operation of the "Autolign" can be carried out in any one of its four modes--1) Autostart, 2) automatic, 3) semiautomatic, and 4) manual--each successive mode allowing for further operator control, with all reported testing being in the Autostart mode. In this mode, setup of mask and microscope is initially required. From then on, the operation is machine-paced, with the entire process being performed automatically; the operator's only functions are those of loading and unloading wafers and verifying alignment at the inspect pause. Allowance is made for the cycle to be stopped at any point by the operator depressing a footpad. The machine cycles continuously and follows the following sequence of operations -- a) rotates wafers into load/unload positions, b) performs the alignment procedure, c) clamps wafer to mask, d) awaits operator verification, e) exposes after step button is depressed, and f) rotates wafers into unload/load positions.

Mask Requirements

To accomplish automatic alignment, the mask targets must first be established for the particular process to be used (e.g., bipolar, MOS, etc.) by exposing wafers throughout their processing sequence to the "Computervision Universal Test Masks" suitable for either the positive or negative photoresist processes. Targets are withdrawn at each step as exposure destroys the aligned acquisition target, rendering it useless for any subsequent alignment. Thus, a multiple target is employed to provide the required target sequence for the process mask series.

Initial concern was with the ability of the mask making industry to perform the task of reticle alignment to the desired accuracy for the number of different targets required in each layer and for the repeatability of the step and repeat equipment required to generate these multiple target evaluation masks (up to five stepping changes of the reticle for each layer are required). This can be seen in Fig. 2.

Figure 2 illustrates a photomask stepped on one of the three stepping systems employed in this mask feasibility study. The first is stepped on the David W. Mann photorepeater, which has a claimed positional precision over a $2\frac{1}{2}$ x $2\frac{1}{2}$ inch area of $\frac{1}{4}$ μ (Photics Research Corp.). The second mask was stepped on the Varadyne laser interferometer photorepeater, which has a claimed programmable resolution over a 5 x 5 inch area of $\frac{1}{4}$ μ (Electromask, Fig. 2). The third mask was stepped on the Jade photorepeater, which has a claimed repeatable image accuracy over a 3 x 3 inch area of $\frac{1}{4}$ μ (Photics Research Corp.). All masks were produced without the aid of photocomposing from individual artworks, with multiple stepping techniques being employed. Masks supplied from the D. W. Mann and laser interferometer systems exhibited stepping accuracies throughout the respective mask series of better than 0.000025 inch and those on the Jade system within 0.00005 inch.

It was concluded from this mask study that most avail-

C³⁰⁷ˀ·⁴⁻¹⁸·⁷⁰·¹ COMPUTER VISION
ELECTROMASK NEGATIVE RESIST MASK 1

Fig. 2. Computervision universal test mask for negative photoresist process.

able systems could possibly give a deviation from primary pattern to stepped in target areas of from ½μ to 1μ mainly due to reticle alignment (more of a problem at only X4 reduction) fitting of the reticle holder and the repositioning of the XY photorepeater stage. This has since been overcome by Computervision in the fitting of the Autolign with a target deviation control that allows the system to misalign by a given dimension.

Further studies of the photomasking process indicated that the finally established target areas, which are to be stepped into a primary pattern area, should be either totally composed at the artwork stage or at the reticle stage by the use of a reticle pattern generator.

Target Evaluation

The standard MOS process used in this target evaluation study has four or five distinct steps, although five or six masks are in fact used, in the following process sequence -- 1) field oxide followed by "P" diffusion mask; 2) diffusion and oxidation followed by gate-contact mask; 3) gate oxidation followed by Contact 1 and/or Contact 2 mask; 4) aluminization followed by metal mask; 5) glassivation followed by pad mask.

The evaluation masks from the second mask onward have a mating target (A) that aligns to acquisition targets (B, BN) etched into the wafer through the first masking operation; therefore, by dropping slices out of the process at each step, the correct acquisition target(s) can be selected.

Figure 3 shows a full wafer after the glassivation stage in this evaluation, whilst Figs. 4-8 show a close view of the alignment accuracies achieved throughout the process procedure. In these alignment illustrations, it can be quite clearly seen that alignment of the die on the left hand side of the wafer showed some deviations, which were measured as follows: Level one - nominal (cross 10μ wide), Level two deviation 1.0μ, Level three deviation 1.5μ, Level four deviation 0.5μ, Level five deviation 0.25μ; a consistent deviation of from 0-0.5μ was seen at the right hand side of the wafer. All additional deviations from the right hand side to the left hand side of the wafer could be traced back to the photomasks.
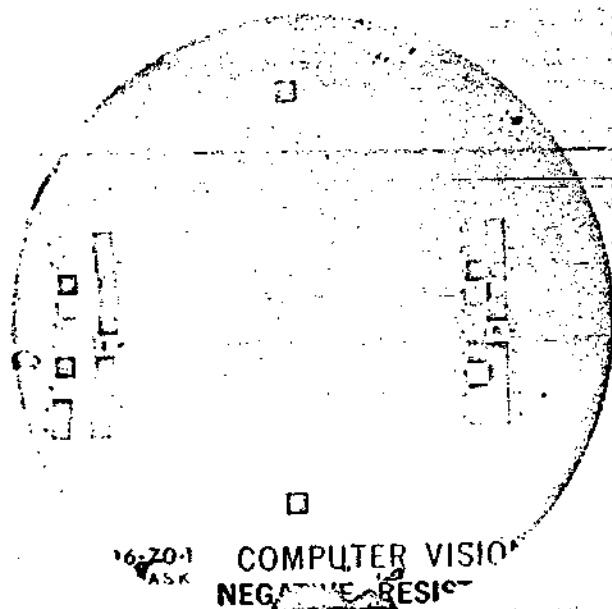
Fig. 3. Evaluation wafer taken through the complete MOS process.
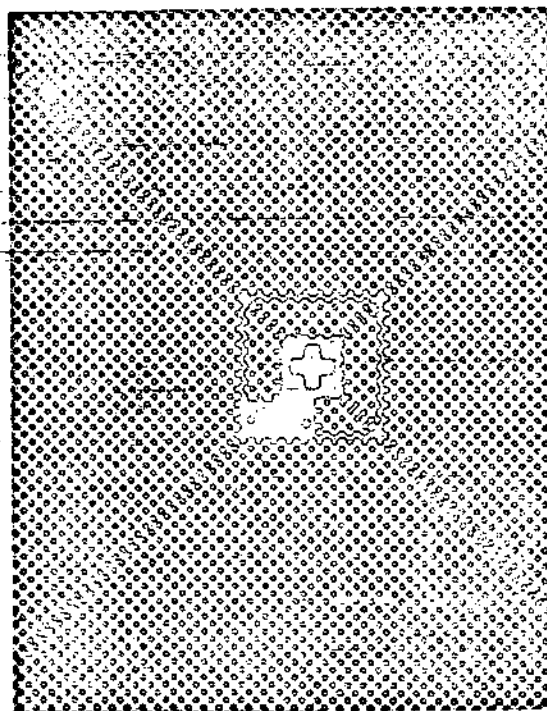
Fig. 4. Photomicrograph of BN target at first process step. Magnification is x300.
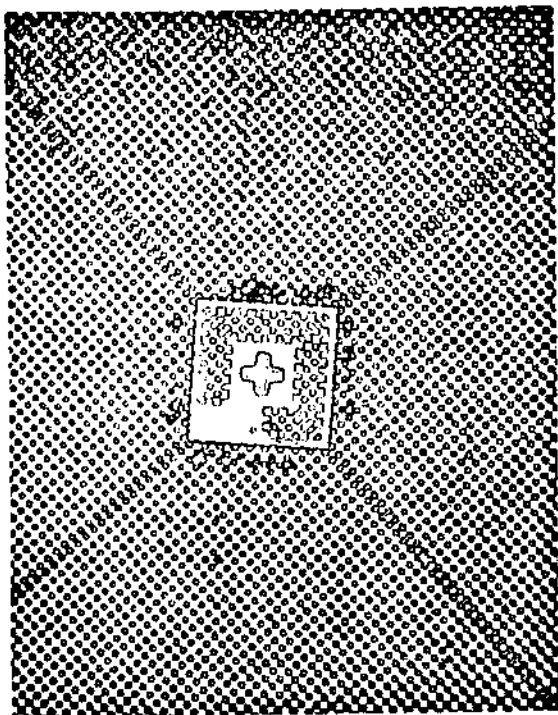
Fig. 5. Target A over BN at second process step. Magnification x300.
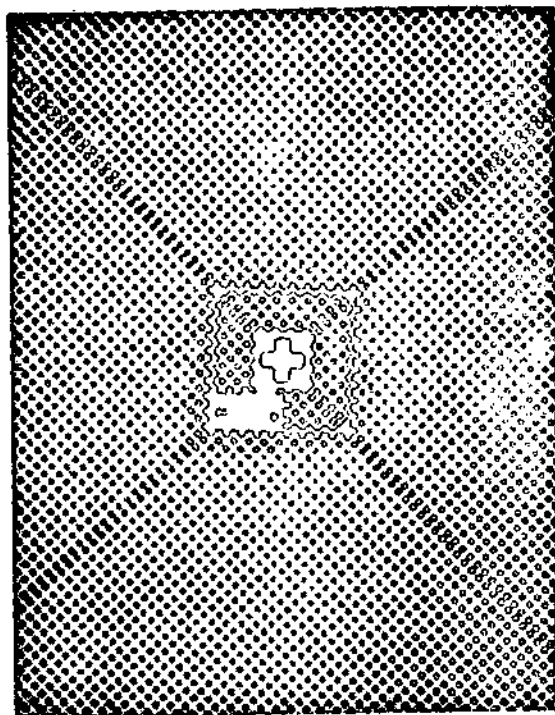
Fig. 6. Target A over BN at third process step. Magnification x300.
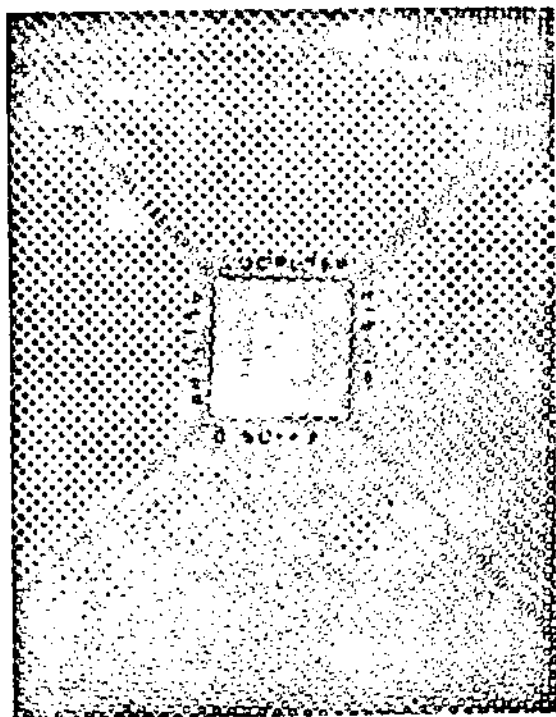
Fig. 7. Target A over BN at fourth process step. Magnification x300.
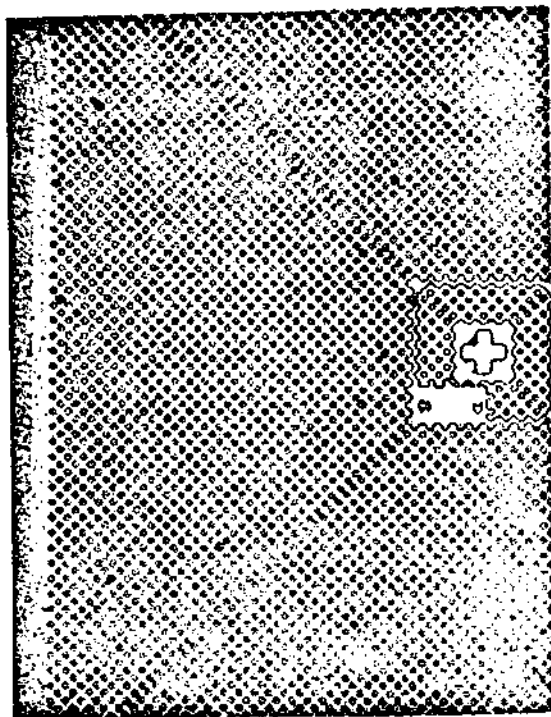
Fig. 8. Target A over BN at fifth process step. Magnification x300.

Determination of the exact alignment target strategy to be employed by study of the processed wafers indicated that the MOS process bestowed itself to a rather simple target strategy--namely, two targets, BN and A, measuring 50 x 50 mils, which are illustrated in Figs. 9 and 10. Table 2 shows target positions, which were established from Figs. 9 and 10. The use of clear areas is to retain the acquisition target until that level alignment has been accomplished. The use of opaque areas is to destroy the aligned images so that no further alignment to that particular target can be performed for a negative working photoresist process.

It was found using 2 inch wafers that an inter-objective spacing of 1.4 inches, corresponding to a similar target separation on the masks (Fig. 11), resulted in adequate alignment accuracy. Layouts of the target and blank positions one to four for both the right hand side and the left hand side of the mask are illustrated in Figs. 12 and 13. These targets and blanks have to be arranged into the right hand side so that the distance between any viewed pair of positions on the "X" axis is different.

Table 2. Target positions.

MASK LEVEL	Position #1	Position #2	Position #3	Position #4
"P" Diffusion	BN	BN	BN	BN
Gate-contact	A	Clear	Clear	Clear
Contact 1 & 2	Opaque	A	Clear	Clear
Metal	Opaque	Opaque	A	Clear
Passivation	Opaque	Opaque	Opaque	A
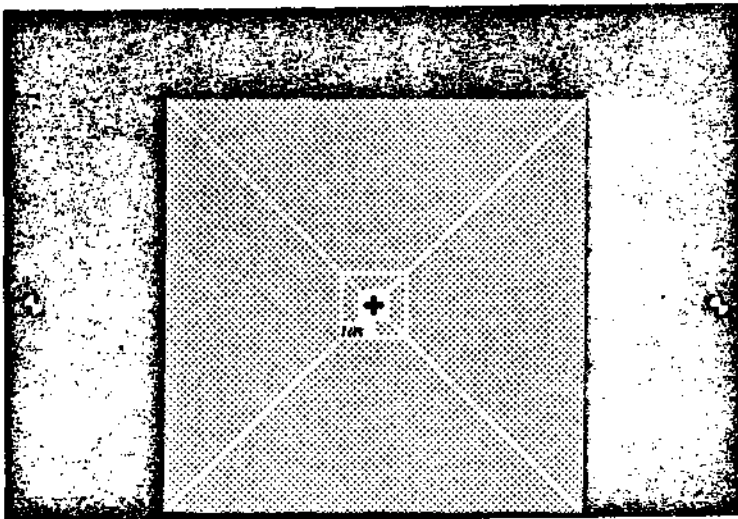
Fig. 9. Photograph from original artwork showing target BN.
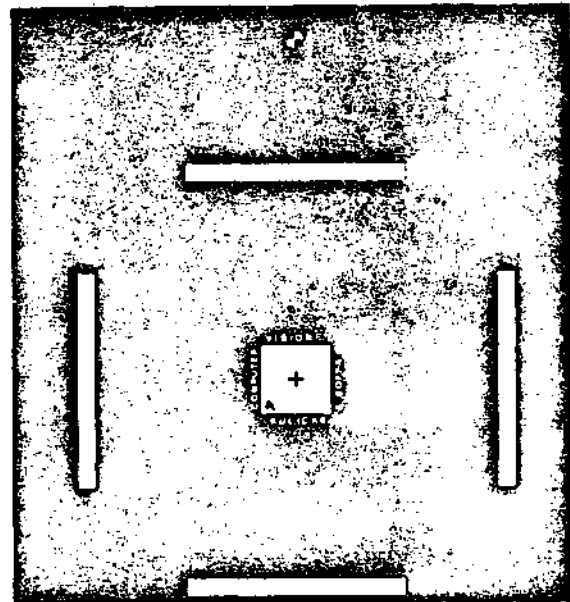
Fig. 10. Photograph from original artwork showing target A.

Fig. 11 *Photomask showing required target positions at 1.4 inch separation.*

Integrated Circuit Manufacture With The "Autolign"

The reticles for the drop-in alignment targets for the MOS/LSI photomasks were made in two different manners -- namely, a set of composite artworks at x500 full size showing the necessary positions of the acquisition targets and blanks, these being reduced to give the final ten reticles, two of which will be stepped into each of the mask layers. Secondly, the individual artworks were digitized, with the composing being done onto paper tape and then fed to the interferometric reticle generator providing the ten reticles required to generate the five layer mask array. Alignment proved to be extremely fast and accurate, giving 100% wafer yield through alignment inspections and improved wafer probe yield of the final devices.

The following photomicrographs (Figs. 14, 15, 16, 17, and 18) show the MOS integrated circuit through its five process steps, along with the circuit alignment target and the "Autolign" acquisition targets.

Fig. 12. *Left hand side of photomask showing position of alignment targets.*
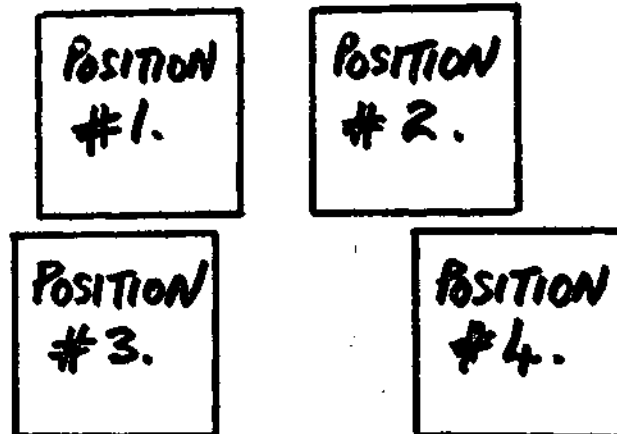
Fig. 13. *Right hand side of photomask showing position of alignment targets.*
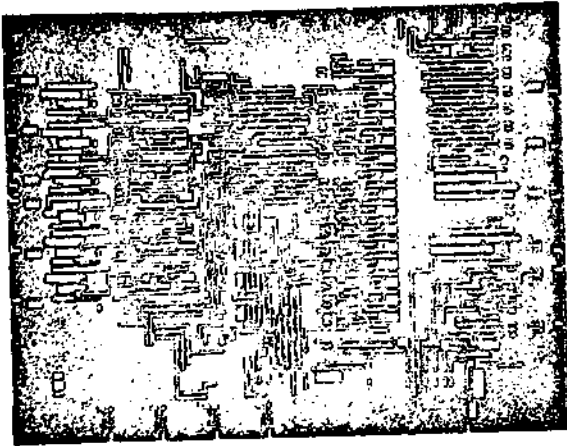
Fig. 14a. *Circuit after P diffusion mask, x40 magnification.*
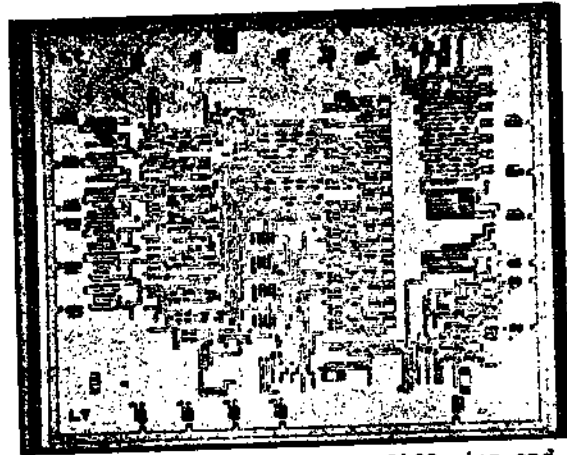
Fig. 15a. *Circuit after P diffusion and gate-contact masks.*
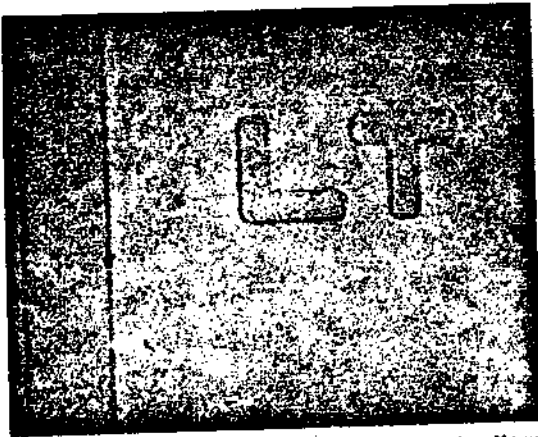
Fig. 14b. *Circuit alignment target. Magnification x375.*
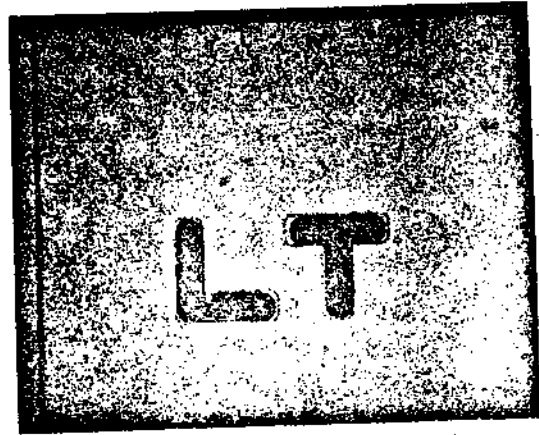
Fig. 15b. *Circuit alignment target.*
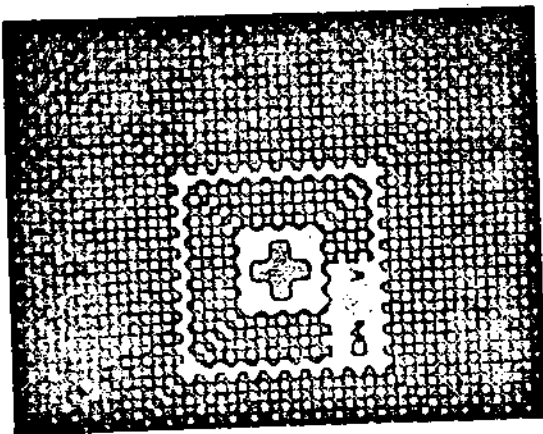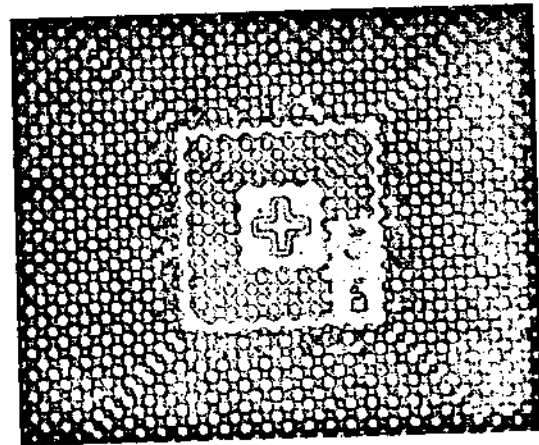

Fig. 14c. *Autolign BN target. Magnification x375.*
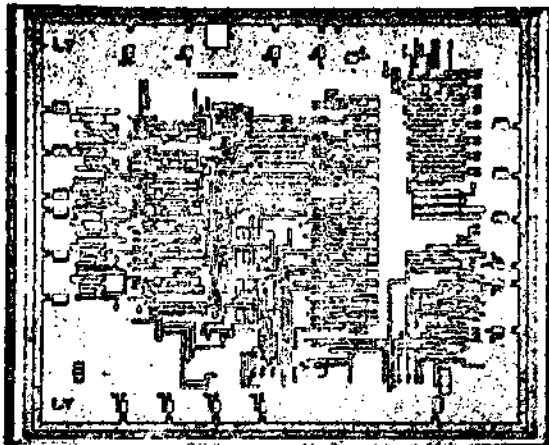

Fig. 15c. *Autolign A over BN target.*

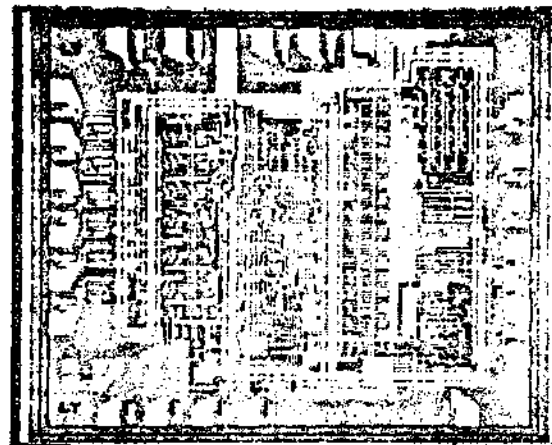**Fig. 16a.** *Circuit after P diffusion, gate-contact and contact masks.*

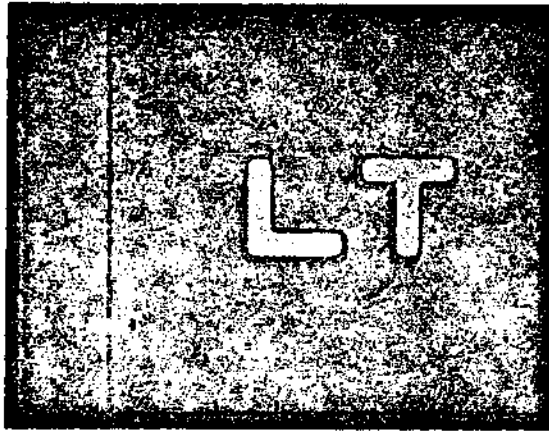**Fig. 17a.** *Circuit after P diffusion, gate-contact, contact and metal masks.*

Fig. 16b. *Circuit alignment target.*
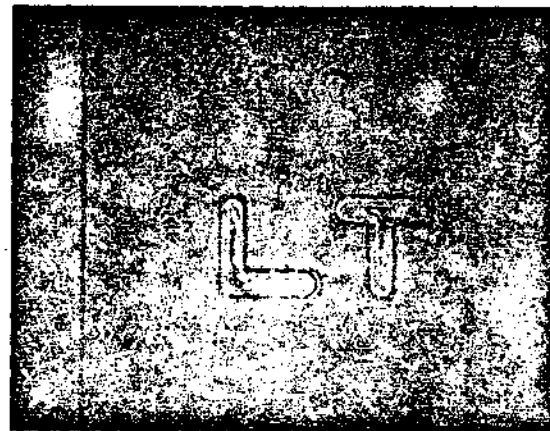
Fig. 17b. *Circuit alignment targets.*
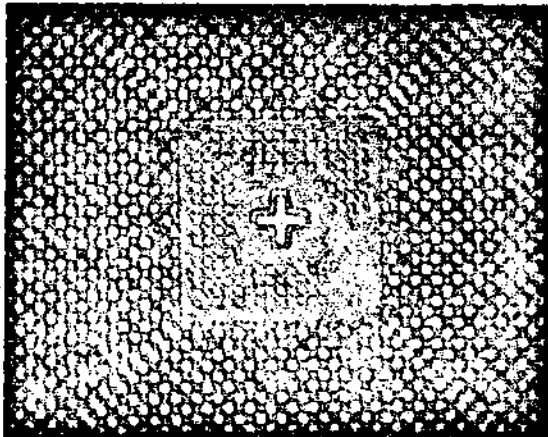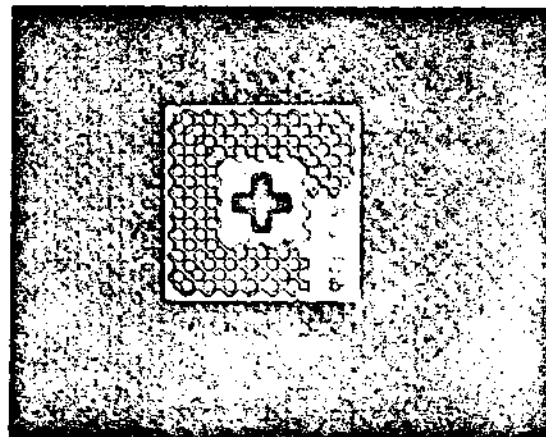

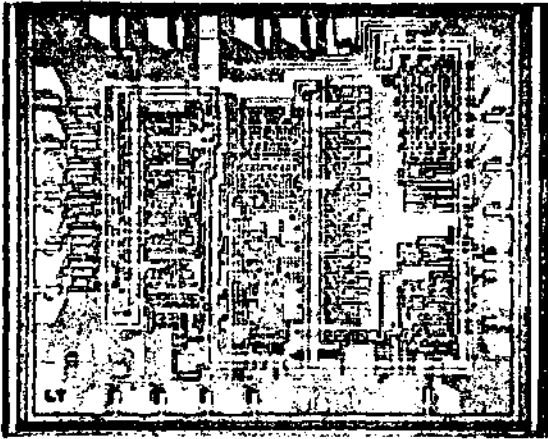**Fig. 16c.** *Autolign A over BN target.*

Fig. 17c. *Autolign A over BN target.*

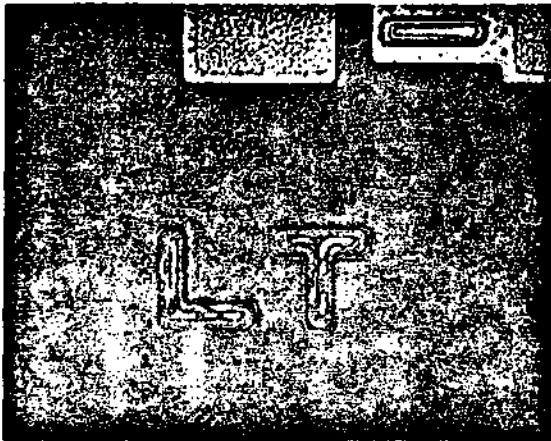Fig. 18a. Circuit after P diffusion, gate-contact, metal and glassivation masks.
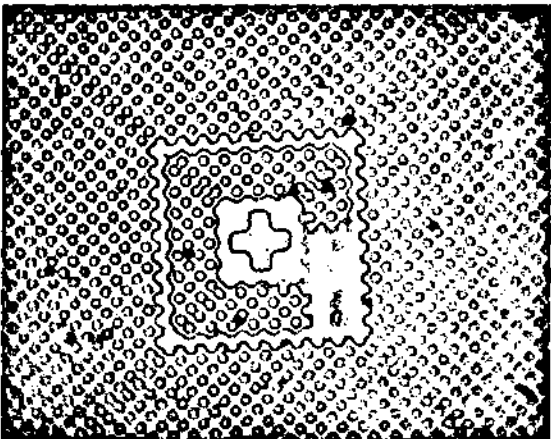

Fig. 18b. Circuit alignment targets.

Fig. 18c. Autolign over BN target.

These photomicrographs clearly illustrate the accuracy of the stepped-in acquisition targets in relation to the primary circuit pattern, producing accurately aligned circuits throughout the mask array.

The maximum misalignment in this circuit was at the contact mask level, this being 0.75 µ, which coincided with the minimum signal and contrast in the oxide layer. This was also seen as the largest misalignment when carrying out the evaluation study.

The maximum alignment accuracy was seen after metallization on both layers four and five, with less than 0.5 µ being the deviation. This was in keeping with the evaluation study and also coincided with the maximum signal and contrast conditions.

Automatic Alignment System Advantages

Production Rate. After the operator became familiar with the Autolign mode of operation, the production rate showed a marked increase over that of the visual circuit alignments in the manual mode. A typical manual alignment time (taken over a 100 wafer run) was 45 seconds; this was reduced to 20 seconds when using the Autolign automatic system. Towards the end of a shift, a noticeable increase in the manual alignment time was observed. This could be directly related to operator fatigue. In the automatic mode, the procedure of loading and unloading the motorized wafer turntable resulted in very little operator fatigue for a much greater number of wafers through the alignment system.

Masks. The amount of usable area given up on a wafer to the acquisition targets was no greater than our present system of row and column alignment targets. The acquisition targets were also found to be quite suitable, when operating an alignment machine in the manual mode, for visual row and column pre-alignment.

While operating the Autolign in its automatic mode, the separation distance between mask and wafer was set to its maximum setting of approximately 0.002 inch, thus reducing the possibility of mask-wafer abrasions. It should be noted that at this separation, the operator is unable to focus on both the mask and wafer to be able to do visual alignment. Should visual alignment be required, the separation distance must be closed until the depth of field of the microscope allows for both the mask and wafer to be seen clearly.

The machine, after performing the alignment task, goes directly into the clamp position and either awaits operator verification of alignment and/or exposes the photoresist coated wafer. This is a very different situation from the manual alignment mode,

where from 2 to 4 clampings are generally made before satisfactory alignment is obtained. Should the acquisition targets be misplaced to the primary circuit pattern by as great a distance as 5 μ, the alignment offset control can be set to the known deviation and result in the primary pattern alignment to within a 1 μ accuracy.

The overall advantages of this alignment system with respect to masks is the much greater usage obtained from the mask due to the noncontact of high spots during the alignment cycle and the fact that only a single clamping is required before exposure. It is estimated, based upon the present usage of the machine, that almost twice the mask life could be obtained.

Yield Improvement. Direct improvements in both wafer yield through the process and die yield at test can be attributed to some of the inherent functions of the system already described -- that is, a) due to the increased separation, no scratching or abrasions to the photoresist layers were detected in this MOS/LSI process; b) due to only a single clamping being necessary, less damage occurs to both mask and photoresist layer on wafer; c) automatic row and column alignment is assured; d) submicron accuracy over the wafer being achieved.

Conclusions From Autolign System Usage

In conclusion, it can be stated that the Autolign automatic alignment system gave consistent accurate alignments to submicron dimensions with the minimum of mask-wafer contact, resulting in a very high wafer yield through post-development inspection. It should be noted at this point that broken wafers that separate the alignment targets can no longer continue through the automatic alignment process.

Cost savings can be made in the areas of greater mask usage, higher production rate, wafer yield improvement, and die yield improvement, which should easily offset the higher initial cost of either purchasing, or retrofitting the K&S 686 to, an Autolign.

During the several months of this evaluation testing, the machine operated with high reliability; the only work being carried out on this system was in updating certain machine functions to the present mode of operation.

It would now be interesting to see this system of automatic image recognition alignment fitted to a 1:1 projection alignment system, resulting in the most effective mask-wafer alignment exposure system.

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SECOND GENERATION AUTOMATED WAFER TO MASK ALIGNERS

by

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Introduction

The manufacture of semiconductor devices has eluded automation in two areas--the alignment of the wafer to the mask in the photolithographic area, and the bonding of the wires from the semiconductor chip to the package in the final packing area. Until recently,.these operations required an operator to view the topology of the device through a microscope and to make a value judgement as to its position with respect to the mask in the case of the photolithographic process, and the bonding tool in the case of the packaging.

Manual bonding is a costly process, since an alignment to an accuracy of approximately ± 1 mil must be made to each output pin of the device; thus, the labor costs for the operation are high. The ultimate solution to this problem does not lie in the automation of the wire bonding process, but in the elimination of the task in its entirety by changing the lead attachment technology, i.e., beam lead or flip chip.

While the task can be eliminated in the packaging of the device, the need for accurately aligning the silicon wafer to the mask appears to be the method by which both discrete and integrated circuits will be produced in the foreseeable future. With packing densities and operating frequencies of devices increasing, the alignment tolerances required are growing more stringent each year. It is obvious that the automation of the critical alignment step in the photoresist line, coupled with the newly emerging wafer handling technology, will drastically reduce the personnel required in the photoresist area and reduce mask costs while permitting greater yields through higher consistencies and reduced handling.

In the past two years, the technology in two fields--automatic alignment and wafer handling techniques--have been greatly advanced. The combining of these technologies has now provided the first mask to wafer aligner that does not require an operator for either loading and unloading wafers or for aligning the wafer to the mask. A cassette containing an entire wafer lot can now be inserted into an automated aligner; then it automatically performs all wafer handling, alignment and exposure. The completed wafer lot (loaded in a cassette) is removed and ready to be developed. The operator need only load and unload the cassettes and change the mask when a new one is required. These operations are accomplished by utilizing Computervision's Super Autolign outfitted with an automatic wafer handling system.
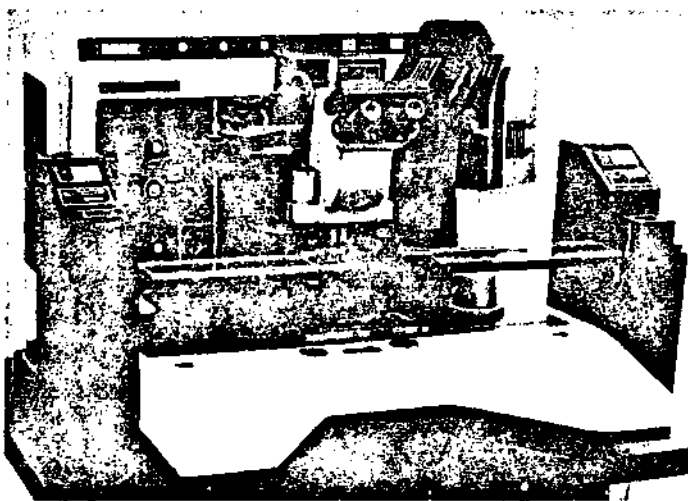

Fig. 1. *Autolign with autoload.*

Work Flow Through the Operatorless Autolign

Figure 1 shows Computervision's "operatorless autolign." The operation of the machine is as follows. The operator loads the mask into place and positions the microscope over the special recognition

targets in the mask (these will be explained in greater detail later in this paper). She then places the cassette containing the wafers to be aligned and exposed into the wafer sender and an empty cassette into the wafer receiver. Cassettes are reset to their normal positions, and the start button is depressed. This first wafer is sent down the track to the turntable, where it is accurately prealigned. This accurate prealignment assures that when the wafer is indexed under the mask, it will require less than 0.020 inch of motion in X, Y or θ for its final alignment. After prealignment, the turntable rotates the wafer under the mask. The automatic alignment system is then activated. The final alignment that takes place at this station is accurate to within 0.85 micron. After the alignment is complete, the wafer is brought into contact with the mask and exposed by an electronically controlled ultraviolet source. The electronic ultraviolet source controller insures that the wafer is exposed properly, regardless of the brightness of the ultraviolet source.

While a wafer is being accurately aligned and exposed, the following wafer is loaded onto the turntable and prealigned. This prealignment is completed before the 0.85-micron alignment and exposure is completed. Thus, as soon as the aligned wafer is exposed, the turntable rotates, delivering the finished wafer to its carrier and positioning the next wafer under the mask. This continues at a rate of one wafer each 15 seconds until the entire run of up to 25 wafers is completed. The total time that is required for the full lot of 25 wafers is approximately seven minutes, including the mask set time. One operator can easily service three such machines. With only one operator, the output of the plant can be as high as one wafer each six seconds.

Automatic Alignment System Operation

The Autolign, manufactured by Computervision Corporation, Burlington, Massachusetts, contains the optics, mechanics and electronics necessary for controlling the wafer feed system and performing the 0.85-micron alignment between mask and wafer. To perform the alignment of the mask to the wafer, the machine requires a pair of alignment targets (one on the left and one on the right) etched into the oxide on the wafer (see Fig. 2) and a complementary pair of targets on the mask (see Fig. 3) for each alignment operation. These targets must be placed onto the mask set that is to be used on the automatic aligner when the masks are fabricated. The first masking operation exposes the targets that are required for subsequent masking levels along with the circuit geometries. When the wafers are etched, the targets are cut into the silicon dioxide. Each of the following masks have a pair of complementary targets in them. The Autolign performs the alignment by viewing the composite mask and wafer alignment target geometries via the optical system and by controlling the X, Y and θ drives until the targets on the mask and the wafer are in precise alignment. When this occurs, the wafer is brought into contact with the mask and exposed.

The optical system on the aligner (Fig. 4) is a standard split field microscope that has been modified by a fibre-optics illumination system and a beam splitter pick-off, which provides the optical detection system with its automation. When viewing through the microscope, the only apparent difference that one observes is a reticle in the right eyepiece. This reticle is used to align the microscope objectives to the targets in the mask. The alignment between the microscope and the mask need only be accurate to ± 2 mils, but it is required for each new mask that is inserted into the aligner.

When the wafer is brought to the mask for alignment, the outputs of the optical transducer are processed by the system's alignment electronics. The electronics have the ability to determine the relative position of the wafer with respect to the mask. The ability to determine relative position rather than just an alignment (go-no go) is important, since it makes it possible to misalign purposely the targets on the mask to those on the wafer to correct for errors in the mask making process. The alignment electronics provide inputs to three servos that position the wafer under the mask. The electronics and servo systems move the wafer in ¼ micron increments. When the wafer is aligned within ¼ micron in the X, Y and θ axes, the servo drives are disabled and the wafer is brought into contact with the mask.

The shutter on the mercury-arc exposure source is then opened, providing the ultraviolet necessary for the photoresist exposure. Rather than using a simple timer, which is currently used throughout the industry, an energy integrator (Autoflux) controls the length of the exposure. When the proper energy level has impinged on the wafer, the shutter is closed and the next alignment is initiated.

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A portion of the alignment target on the wafer must be viewed through the alignment target on the mask for the electronics to generate the drive signals. This requires that the wafer be prealigned to an accuracy that is equal to or better than the size of the alignment target. The alignment targets measure approximately 25 mils; hence, the wafer handler must be capable of this accuracy. With the proper tolerance on the diameter of the wafer (± 10 mils), this accuracy can be easily obtained.
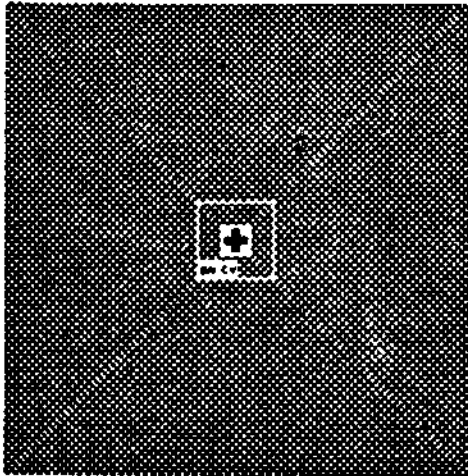

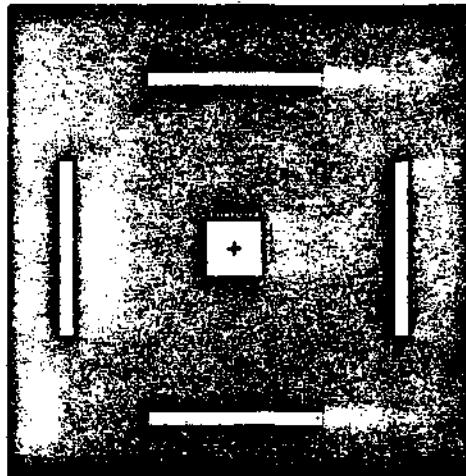Fig. 2. Alignment target on wafer.

Fig. 3. Alignment target on mask.

Wafer Feed System

The wafer feed system is composed of three main subsystems--loader, unloader and prealigner. Both the loader and unloader accept a vertically loaded cassette. This form of the cassette is desirable, since it mates well with other automatic equipment presently used in the photoresist area--namely, resist spinners and developers. In the design of a process line, the form of the wafer carrier is less important
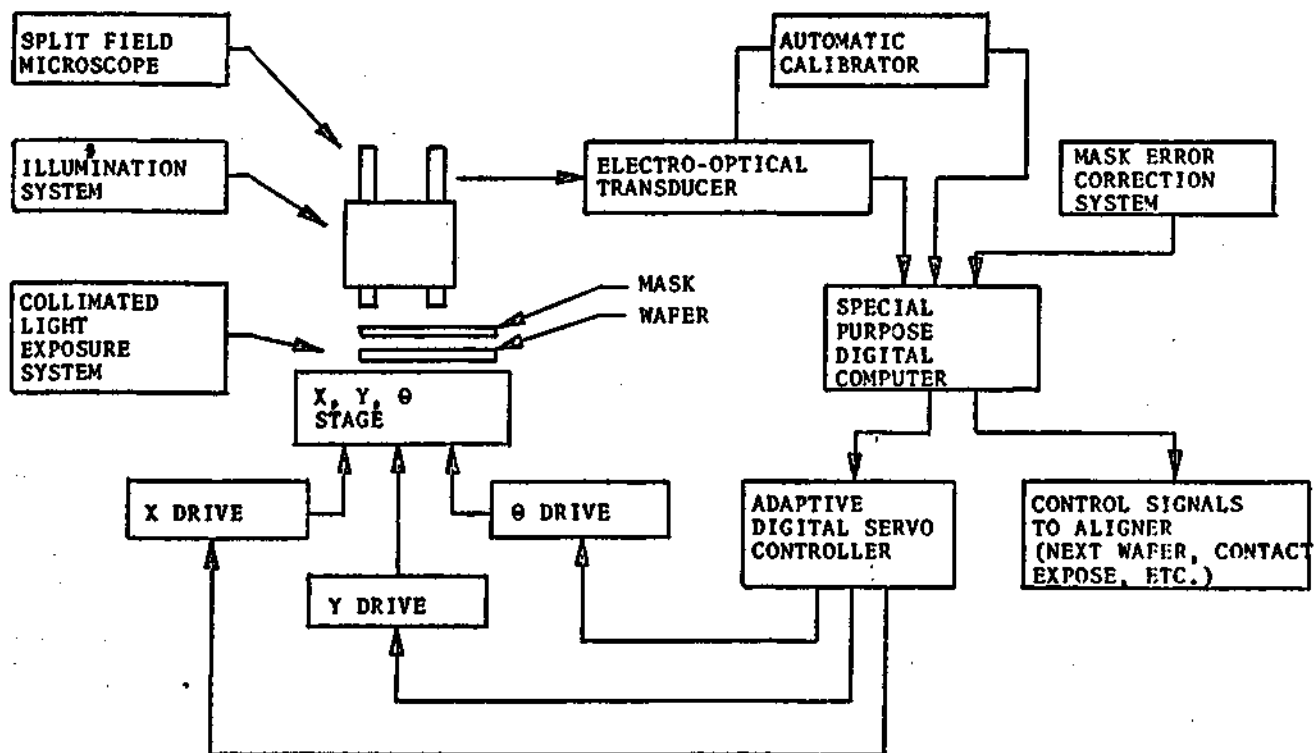

Fig. 4. Automatic aligner.

than the ability of the carrier to mate well with various types of automated equipment.

The loader, unloader and prealigner move the wafer about on an air bearing. The loader accepts a fully loaded cassette of 25 wafers. Upon command, it transports the wafer to be processed to the prealigner station. At the prealignment station, the wafer is rotated until its flat is accurately positioned with respect to a fixed frame of reference in the machine. When this is accomplished, the turntable rotates the prealigned wafer to the final alignment station in the machine. After completion of the alignment and exposure, the wafer is returned to the prealignment station. It is carried by the unloader to the cassette containing the processed wafers. This wafer flow continues until the initial cassette containing the unprocessed wafer is empty and the processed wafer cassette is full. At this point, the operator removes the processed wafer cassette, transfers the empty cassette from the loader to the unloader, and is then ready to process the next lot of wafers.

What Is Gained By Automation?

The semiconductor industry is constantly striving to achieve two goals--increased yields and reduced costs. Automation is the means by which these goals will be achieved. Let us examine the impact that the operatorless aligner has on the yield and cost of a semiconductor device.

Two of the key parameters that affect the ultimate cost of producing a wafer are the amount of labor required and the rate at which masks have to be replaced due to wear. It is obvious that the labor required to align and expose wafers is drastically reduced via this type of automated equipment. The maximum rate at which wafers can be aligned and exposed manually is approximately one each 40 seconds for 2-micron alignments and one per minute if alignment accuracy is to be held to 1 micron. In contrast, a single operator can produce one wafer every six seconds if she controls three operatorless aligners. Hence, the labor requirements are reduced approximately 10 to 1. If other equipment in the plant uses the same wafer cassettes, labor requirements will be further reduced, since the efficiency of the material flow through the plant will be increased.

The second large cost saving that occurs is due to increased mask life. Mask life varies inversely to the number of wafer-to-mask contacts. It is additionally affected by the abrading of the mask by the wafer when high spots on the wafer rub on the mask as the wafer is moved to its final alignment position. An operator doing a manual alignment wants to keep the separation between the mask and the wafer low, since a high powered microscope has a small depth of field. This small separation causes the wafer to abrade the mask. Because the operator has a focus problem (she cannot focus on the mask and the wafer concurrently), she will probably not align the mask to the wafer properly the first time. In fact, the average operator will contact the mask to the wafer 3-4 times before she is satisfied with the alignment.

The automatic aligner is not plagued by these problems. It aligns the wafer to the mask with the wafer out of focus. Thus, all abrasions are eliminated and only a single contact is required per alignment. Eliminating the need for working at close separations and contacting only once per alignment causes the mask to have at least twice the life when compared with manual aligner masks. The savings made due to increased mask life alone can pay for the machine in less than one year.

Two factors that affect yields in the semiconductor industries are rejects due to poor handling and alignment inaccuracies. These two problems are eliminated with the operatorless aligner. Each time a wafer is handled, there is high probability that some area on it will be destroyed. By utilizing automatic wafer handling techniques on the aligner, two manual transfers are eliminated (loading the wafer onto and removing it from the machine). Since this carrier can be used as the input and output of other equipment in the wafer processing area, manual transfers can be reduced to a fraction of their present number.

Of the many factors that affect yield in the semiconductor industry, alignment accuracy is very important. Although most manufacturers inspect wafers for acceptability and recycle out-of-tolerance alignments, more completed devices would pass final inspection if the alignment accuracy was increased and the alignment distribution was narrowed. Although an operator may do a very good job for periods of time, the fatigue and boredom of the alignment task causes her performance to be erratic over long periods. In addition, training an operator to perform accurate alignments is a considerable expense.

Automatic alignment provides excellent alignment consistently. This consistency eliminates one of the variables in the process, thus providing yield increases. In addition, the fact that less damage is done to the mask per alignment means that fewer devices will be lost due to mask defects. The improvement in yield that will occur from previously mentioned factors will greatly depend on the semiconductor product and the personnel producing this product. In general, it is common for the savings per year due to yield improvement alone to exceed the cost of the equipment.

When one considers that three operatorless-Autoligns have the production capacity of approximately ten manual aligners, will increase the production yield and require one-tenth the personnel, it can clearly be seen that the amount of manual alignment will decline and give way to more automated techniques.

Kenneth Levy is Product Line Manager in Computervision Corporation's production automation area. He heads the team that developed the Autolign automated mask aligner and is personally responsible for a number of patents applied for on the Autolign; he invented several of the techniques that made this product possible.

APPENDIX B

AN AUTOMATED CVD SYSTEM

(Reprinted from Motorola Final Report on
Contract AF33615-68-C-1483)

2.0 AUTOMATIC CONTROL

2.1 SCOPE OF WORK

The scope of work includes developing in-process control techniques for the automatic control of: (a) flow rates, composition, and distribution of the incoming gas, (b) all temperature and time factors, (c) gas phase surface precleaning, and (d) impurity profile in the epitaxial layer.

2.2 GENERAL CONSIDERATIONS

The task is basically one of complete automation of the epitaxial process to include the parameters of time, temperature, gas composition, and gas flow. It is not feasible at this time to consider a continuous process in the same reactor, but rather to consider epitaxial growth as a batch process. Reproducibility of growth parameters from run to run and stability of these parameters within a run will be of the most significant value to the device engineer. The evaluation technique will be checked to insure that the evaluation instruments have sufficient precision to permit an objective evaluation of the automated system.

Clocks and timing devices have been available for many years that will permit accurate timing and sequencing of the epitaxial process. Similarly, developments in optical brightness sensors in the last 10 years have led to automatic control of wafer temperature. Epitaxial systems are now sold with these two types of automatic control.

Electronic control of gas composition and flow rate in the epitaxial process is necessary for two reasons: (1) Manual control is no longer adequate for the precision required, and (2) Electronic

sensors and control devices are available to precisely control flows in the range used in the epitaxial process. Most of the engineering effort in this program has been devoted to the automation of the gas control system. Additional cost of the system automation should not exceed $10,000 above the cost of an all-manual system. For example, if a commercial epitaxial system costs $30,000 (excluding RF generator), a totally automatic system should not exceed $40,000 in cost. This goal is practical, especially with recent instrumentation improvements.

Evaluation of the epitaxial film parameters of thickness and impurity concentration will measure the practicality of an automated system. Ultimately, it would be desirable to measure these parameters in-situ during growth. This possibility will be considered in the design of the radiant heated system. In-situ evaluation will not affect the actual quality of the material; however, it will serve to increase the yield and productivity.

2.3   ANALOG CONTROL OF FLOW-SYSTEMS

2.3.1   Introduction

In general, there are three types of control techniques that are available for process automation. These are:

(1) Analog computer control,

(2) Digital computer control,

(3) Combinations of analog and digital control - sometimes referred to as a supervisory control.

Analog control was selected for this work due to its simplicity, availability, and relatively low cost. Cost is a

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valid requirement when the high initial investment in a computer and software program are considered. A digital system does have the advantage of ultimate electromechanical simplicity and programming flexibility. These advantages can be quickly lost, however, in the initial system complexity.

2.3.2   Component Selection

2.3.2.1   Flow Sensor

The requirements of a sensor for a feedback control loop are:

(1)   Voltage or current output must be proportional to gas flow through the sensor.

(2)   Low dead volume in the sensor.

(3)   Rapid transit time of gasses through the sensor.

(4)   Accuracy and reproducibility should be within 0.5 percent of the full-scale reading.

(5)   Short response time to actual flow variations.

(6)   Pressure insensitive or pressure compensated.

(7)   Temperature compensated.

(8)   Minimal cost.

Two types of flow sensors are available for flows of less than 1,000 cc/minute. These are the differential pressure sensors and thermal conductivity sensors. The pressure differential units have a fast response time and good reproducibility,

but they are not pressure insensitive and generally have excessive dead space and high gas transit times. The thermal conductivity sensor has all the advantages of the differential pressure type, and depending on its design, the response time can be kept to less than 10 seconds.

2.3.2.2   Flow Control Valves

Two possible types were considered:

(1)   A motor or servo-driven needle valve.

(2)   An air pressure actuated needle valve.

Both types of valves will accomplish the desired regulation of gas flow, the primary requirement being smooth control over the usable range of the valve. In addition, the valve must adapt to the output of available transducers. The Brooks air-actuated ELF needle valve was chosen for this task.

2.3.2.3   Time and Sequence Control

Programmed time control is available in several types of commercial timers. Some criteria are:

(1)   Preset programming in the form of a tape, card, etc. These programs should be easily changed.

(2)   Flexibility and simplicity. At least 10 separate on-off circuits should be programmable on an independent basis.

(3)   Reproducibility of the time intervals within ± 5 seconds.

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2.3.2.4   Wafer Temperature Control

An optical sensor and proportional control loop similar to those used at present on Motorola's production systems will be used for temperature control. A Leeds & Northrup "Spectray 90" optical sensor provides the input signal to a Motorola "Veritrak" proportional controller.

2.4   ASSEMBLY AND TESTING OF A SINGLE CONTROL LOOP

Elements selected for the prototype control loop were:

(1)   A mass flow transducer (Hastings-Raydist).

(2)   A pneumatically activated needle valve (Brooks).

(3)   A current-to-pressure (I/P) Transducer (Moore).

(4)   A proportional controller (Motorola "Veritrak").

Figure 2 is a schematic drawing of a single flow control loop set up in parallel with a rotameter, both feeding an absolute displacement flow meter (Figure 3). This arrangement was used to characterize the automatic loop and compare it with rotameter control.

The mass flow transducer was evaluated to determine its precision, repeatability, and response time. Figure 4 is a comparison of the characteristic of a glass tube rotameter with manual flow control to that for a proportional control loop. The actual flow rate of nitrogen was measured on the absolute displacement flow meter shown in Figure 3.
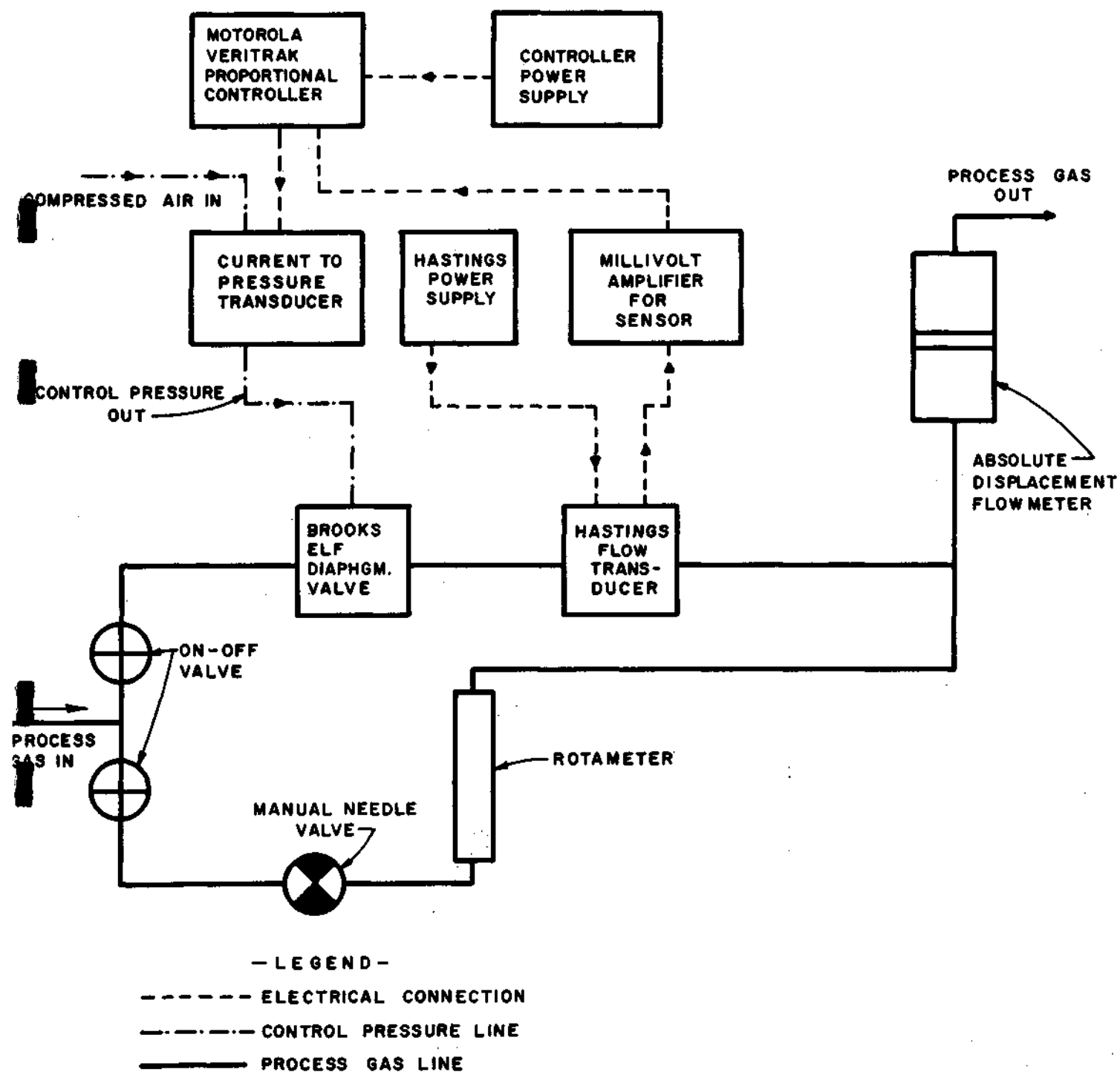
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Figure 2. Block Schematic of a Single Analog Control Loop Set Up For Comparison With a Rotameter

7751-12-8

SUPPORTING CASE

GLASS TUBE

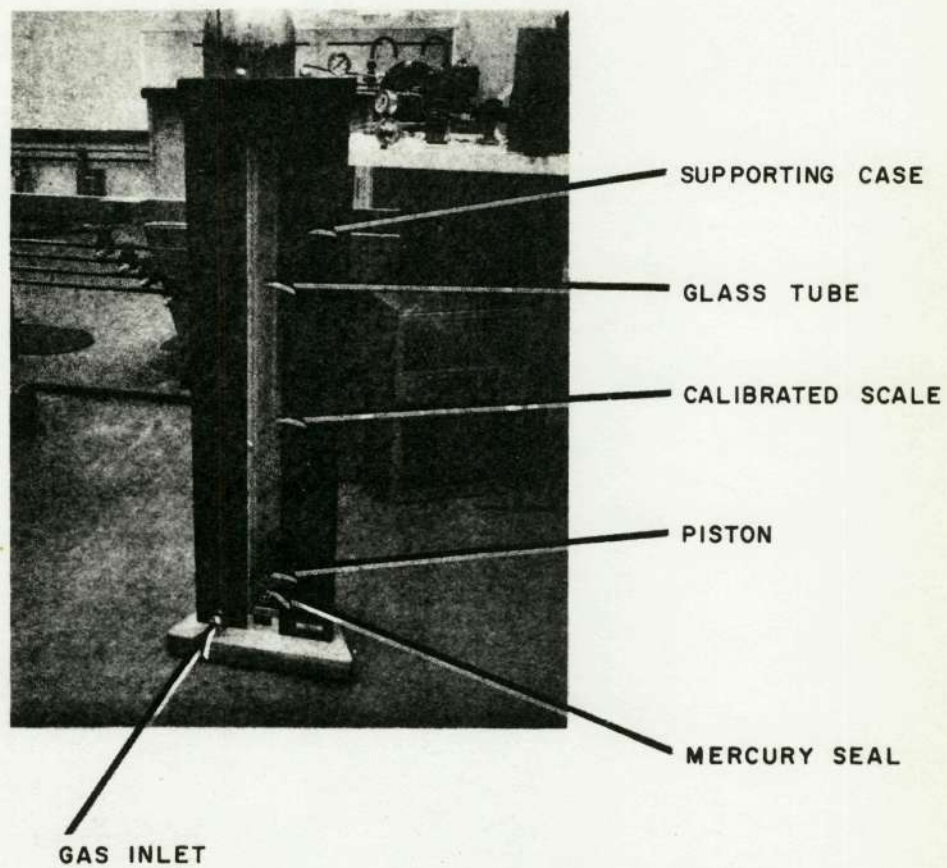CALIBRATED SCALE

PISTON

MERCURY SEAL

GAS INLET

Figure 3. Volumetric Gas Flow Meter Utilizing
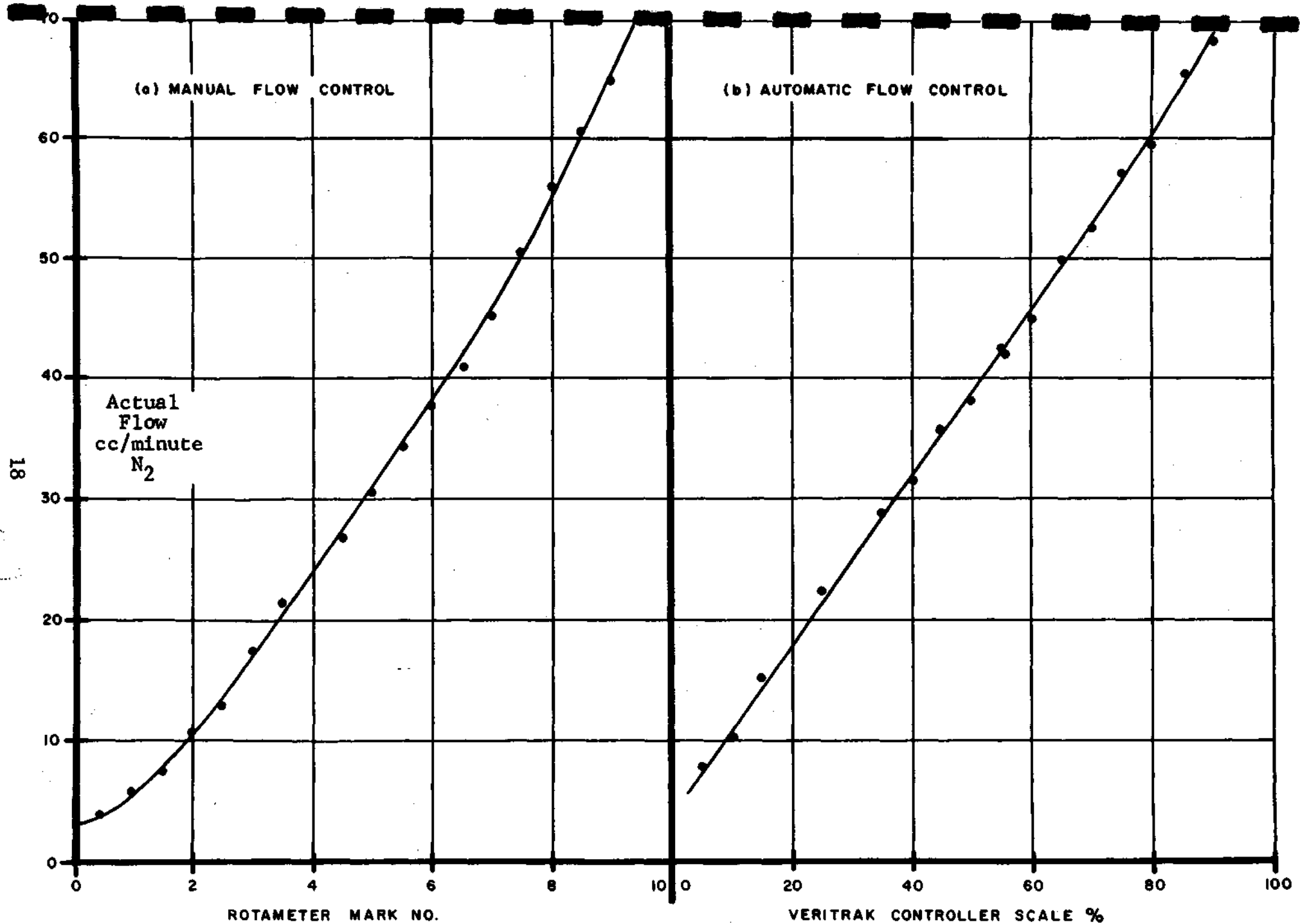a Mercury Sealed Piston

Figure 4.   Comparison of Flow Characteristics
by Automatic and Rotameter Methods

7410a-7-8

The characteristic curves in Figure 4 show that the linearity of the mass flow transducer is better than the rotameter tested over the same range. The mass flow transducers were found to be as reliable as the rotameters in obtaining precise flows at a particular scale setting in "reset" tests. That is, the mass flowmeters had equal precision in returning to a series of setpoints. The points on Figure 4 were generated by first setting the mark number or the scale percent. The flow was then measured on the volumetric flowmeter.

The mass flow transducers were tested for time response following a large step-function change in flow. Figure 5 is a plot of relative response to a step-function change. The response is exponential with a time constant of 8.2 seconds. A similar time response was obtained when the flow was stepped up or down. The time response is somewhat longer than desired, but the analog controller is adjustable for proper damping and maximum control response.

2.5   DOPING GAS FLOW CONTROL

The impurity concentration in the epitaxial layer was established in the system covered in this work through a dilution system shown schematically in Figure 6. This technique is used to cover a very wide range of impurity concentration. Doping gas (such as 0.01 percent diborane in hydrogen) is mixed with diluent hydrogen and a portion of this mixture is then injected into the reactor mainstream. For purposes of control, a single variable can be derived that shall be referred to as the "dope number." The dope number is derived by considering the flow and concentration relationships in Figure 6.

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RESPONSE TIME = 8.2 SECONDS
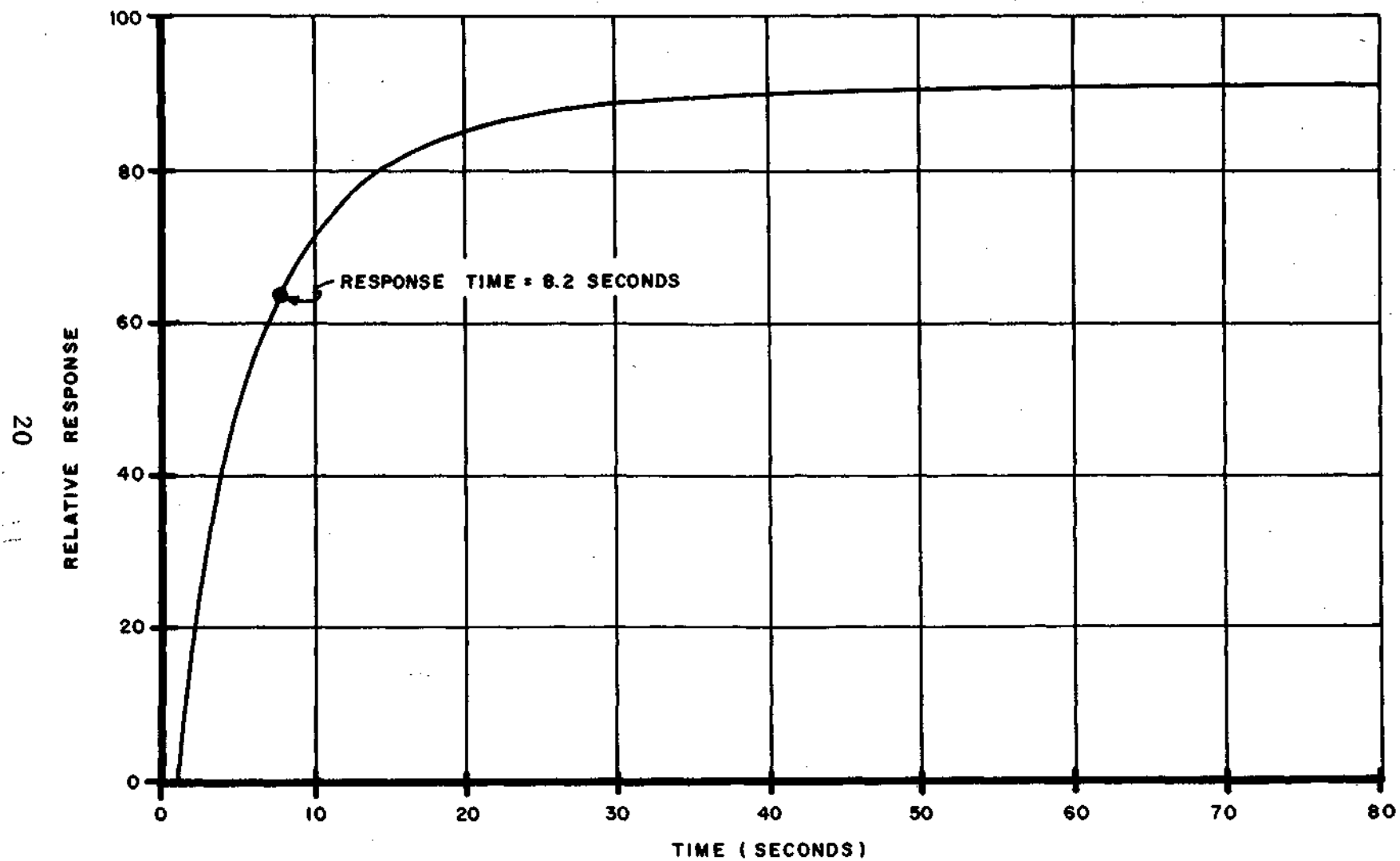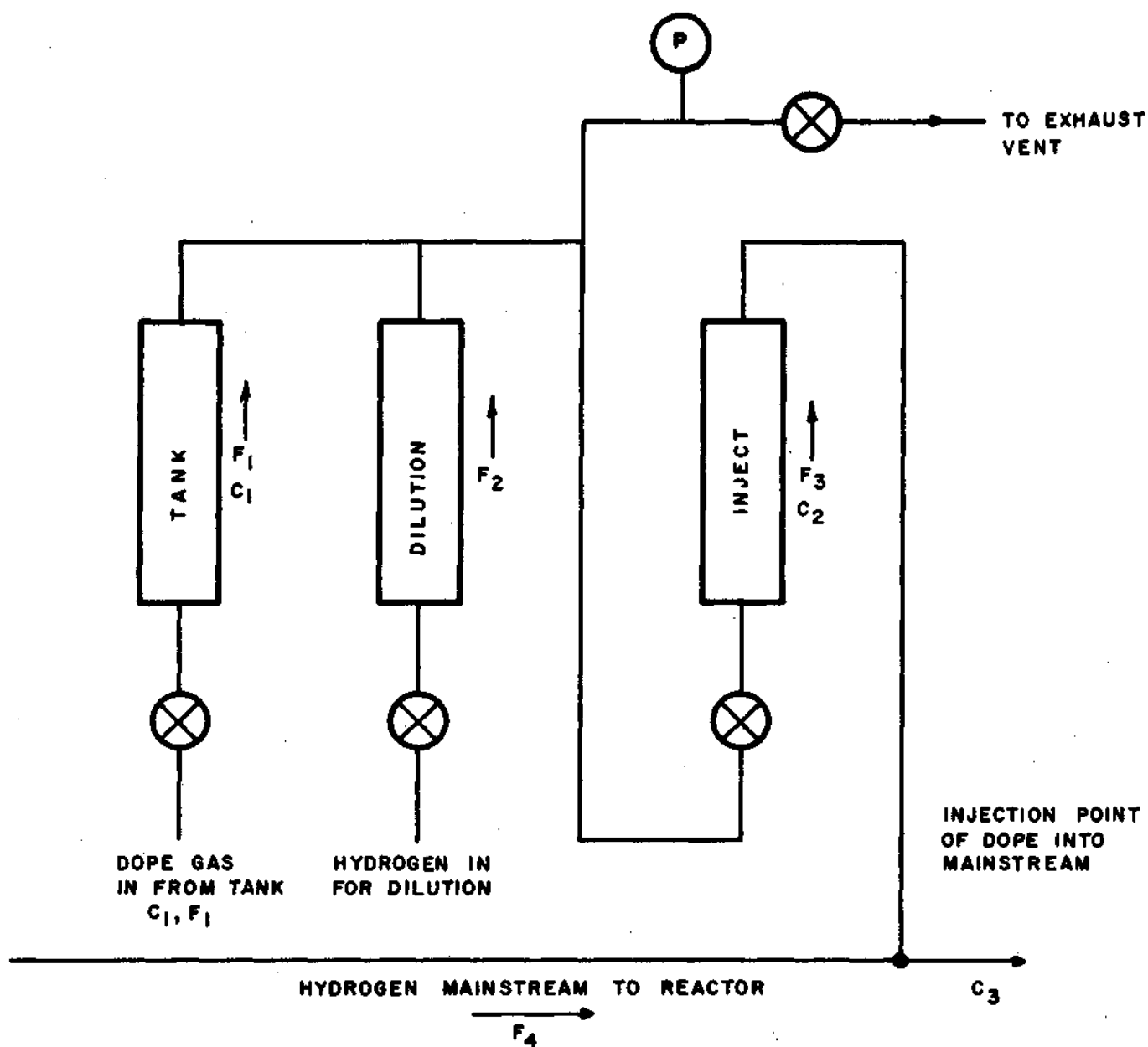
RELATIVE RESPONSE

TIME (SECONDS)

Figure 5.   Transient Response of Mass Flow Meter
Type LF-100

7412-7-8

Figure 6. Method of Dilution for Dope Concentration Control

C_1 = Dope bottle impurity concentration
C_2 = Dope concentration in inject flow meter
C_3 = Dope concentration in mainstream to reactor
F_1 = Tank flow
F_2 = Dilution flow
F_3 = Inject flow
F_4 = Mainstream flow

P PRESSURE GAGE
⊗ METERING VALVE
▢ FLOWMETER

From Figure 6,

(1) $\quad C_2 = C_1 \left(\dfrac{F_1}{F_1+F_2}\right)$

(2) $\quad C_3 = C_2 \left(\dfrac{F_3}{F_3+F_4}\right)$

(3) Substituting 1 into 2,

$$C_3 = C_1 \left(\dfrac{F_1}{F_1+F_2}\right)\left(\dfrac{F_3}{F_3+F_4}\right)$$

(4) If $F_4 \gtrless 100 \ F_3$, then,

$$C_3 \simeq C_1 \left(\dfrac{F_1}{F_1+F_2}\right)\dfrac{F_3}{F_4}$$

(5) If F_4 and C_1 are held constant, as is the case in normal epitaxial runs, then:

$$C_3 \simeq K \left(\dfrac{F_1 \ F_3}{F_1 + F_2}\right) \quad \text{where } K = C_1/F_4$$

(6) The concentration of dope entering the reactor becomes

$$C_3 \equiv \text{dope number} = \dfrac{F_1 \ F_3}{F_1 + F_2} \quad \text{or,}$$

$$\text{Dope No.} = \dfrac{\text{"Tank" } \times \text{ "Inject"}}{\text{"Tank" } + \text{ "Dilution"}} = \dfrac{T \times I}{T + D}$$

where

Tank = the flow rate of doping gas from a cylinder

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Dilute = the flow rate of diluent hydrogen
Inject = the flow rate of diluted mixture injected
into the mainstream.

The dope system flows are related according to this simple formula. For automatic control, this relationship must be maintained constant, or varied according to a fixed schedule to change the doping level in the epitaxial layer.

For the purposes of deriving separate signals for the three flows, the dope number equation must be solved in the inverse form. There is no unique solution in this form and two of the three independent variables must be specified to determine the third. The ideal situation would be a single input variable which produces three independent control setpoints for tank, dilution, and inject flows. To accomplish this, a small analog computer module was developed which generates three control functions in response to a single input function. Two restrictions were necessary:

(1) The dope number must be variable as a predetermined function of time.

(2) The relationship between the single input variable and the actual resulting dope number must be simple enough to allow reasonable accuracy over the entire range. This required dope number has been determined to vary from 0.0005 to 100, or a 200,000:1 ratio. This required ratio was estimated by considering the fact that the carrier concentration must vary between $1 \times 10^{14}/cm^3$ and $2 \times 10^{19}/cm^3$.

The first requirement above was met by using a curve-following instrument as a time-function generator input to the analog module. The DATA-TRAK, made by RI Controls, Inc. is such an instrument. The second requirement necessitates careful design

of the analog module so that the functions which are generated result in a dope number proportional to the logarithm of the input. The logarithmic function is the only one which gives sufficient range and yet maintains the required accuracy.

By graphical analysis and experiment it was established that a combination of a modified reciprocal function for the dilution flow rate and an exponential function for the inject and tank flow rate results in a very close approximation to the desired relationship. Flow meter calibration curves must be factored into this relationship. Table I is a tabulation of the calculated controller scale settings required for an exact logarithmic dope number relationship in intervals of 10 percent of the input variable. Zero values of the inject and tank flow scale settings correspond to flow rates of 4.0 cm^3/minute, and 100 percent to 250 cm^3/ minute. Zero on the dilution flow scale corresponds to 6 liters/minute and 100 percent to 32 liters/minute.

TABLE I

DOPE NUMBER AS A FUNCTION OF THE SINGLE INPUT VARIABLE

Input Percent	Dilution Percent of Scale	Inject Percent of Scale	Tank Percent of Scale	Dope Number
0	100.0	0.0	0 0	0.0005
10	53.8	0.45	0.45	0.0013
20	31.5	1.3	1.3	0.0036
30	23.1	2.8	2.8	0.0097
40	17.7	5.1	5.1	0.026
50	14.4	9.1	9.1	0.071
60	11.5	15.2	15.2	0.19
70	8.6	25.2	25.2	0.51
80	5.8	40.3	40.3	1.4
90	2.9	63.4	63.4	3.7
100	0.0	100.0	100.0	10.0

The dope number was calculated from the actual flows corrected for specific flow meter characteristics. Figure 7 is a plot of these curves and illustrates how closely they approximate reciprocal and exponential functions. Figure 8 is a plot of the logarithm of dope number as a function of the actual percent of input. Figure 8 is also a graphical representation of the data of Table I and shows how an extremely wide range of dope numbers can be obtained while maintaining error at or below ± 5 percent between the input variable and the actual dope flows.

Figure 9 shows a detailed plumbing diagram of the epitaxial system as it was assembled.
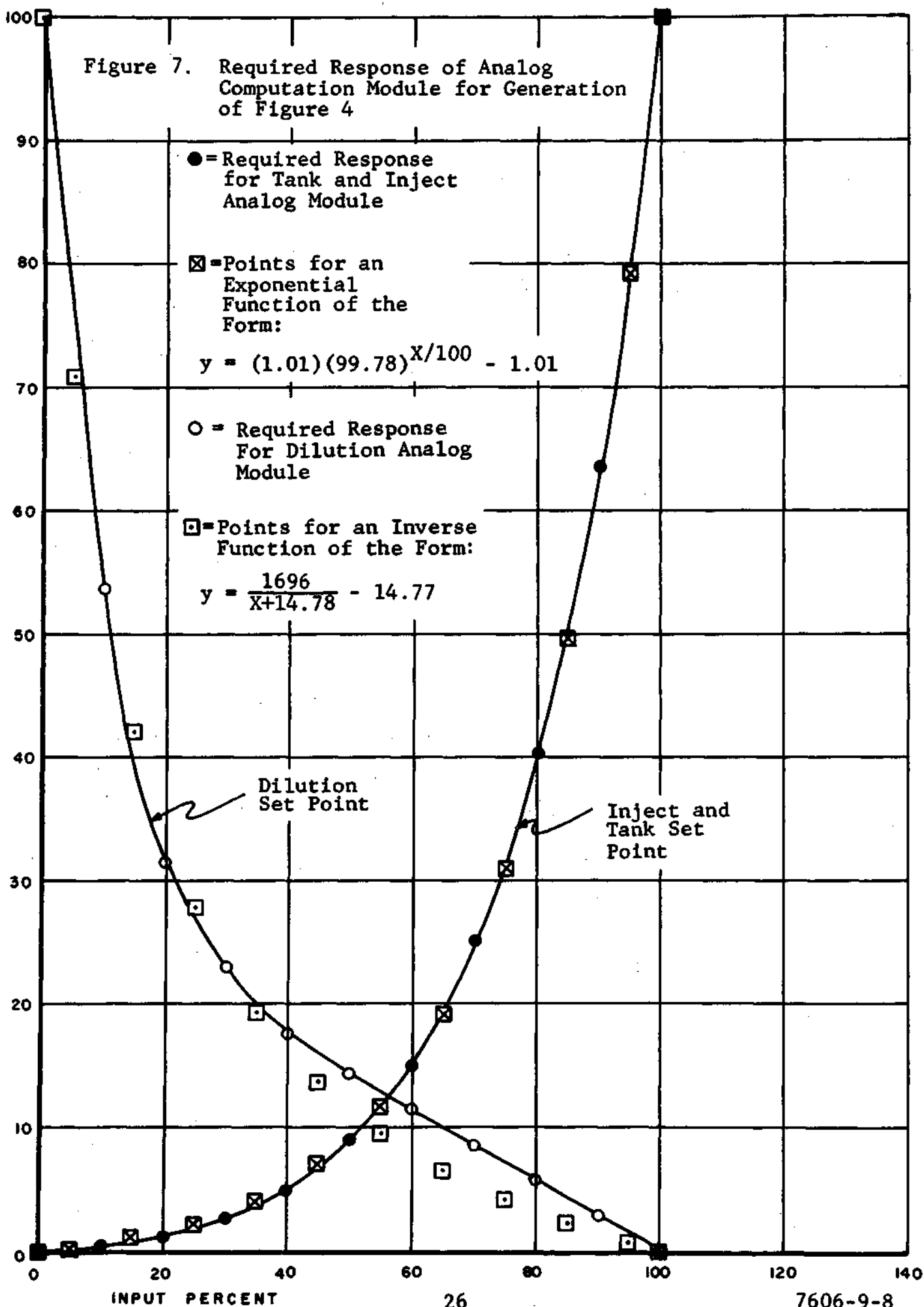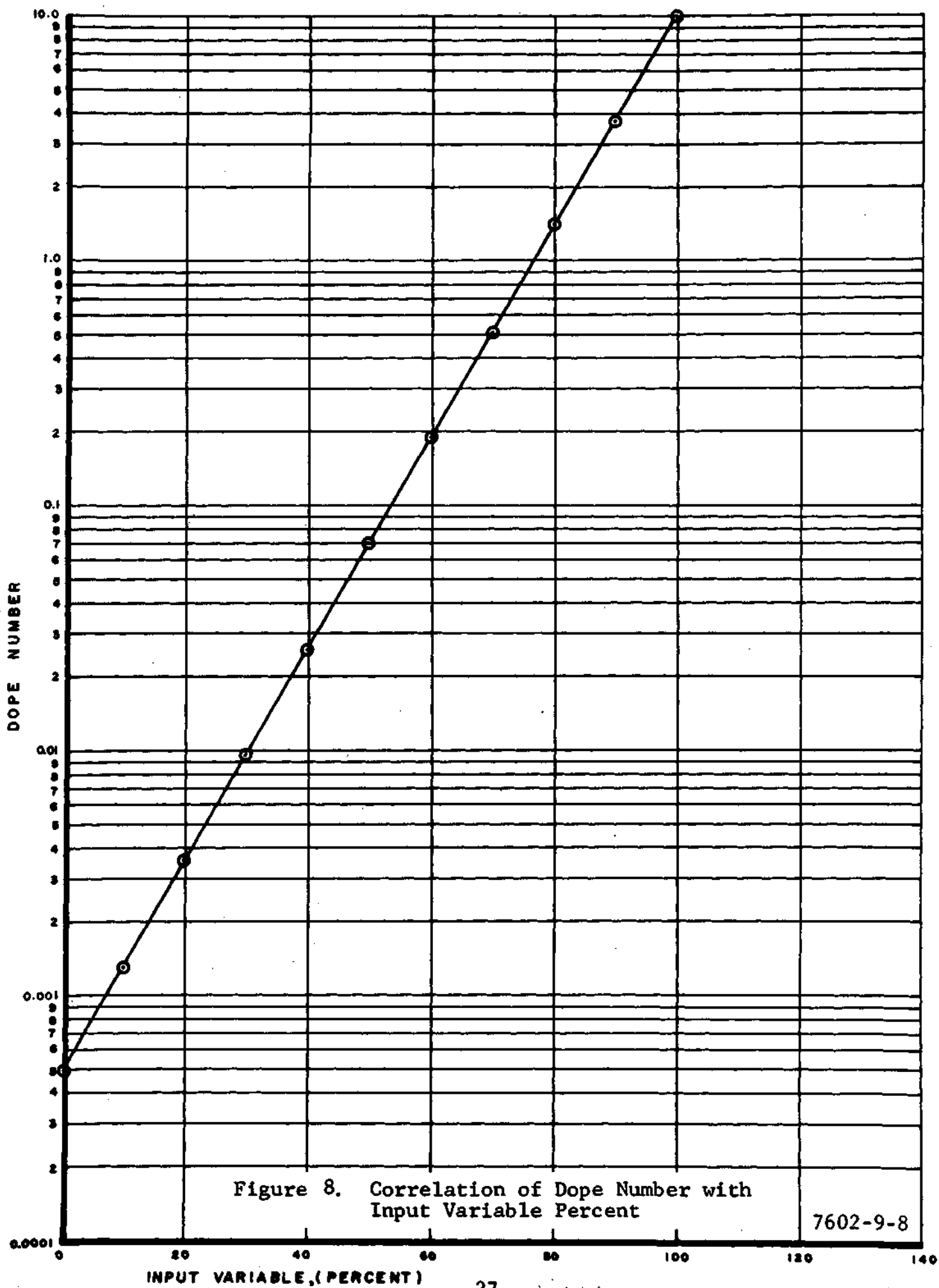
Figure 10 shows a block schematic of the control system.

For time control and valve sequencing logic, the 12-channel card programmer shown in Figure 11 was employed. Table II is a channel assignment for the programmer that will perform all major functions of a typical epitaxial growth cycle.
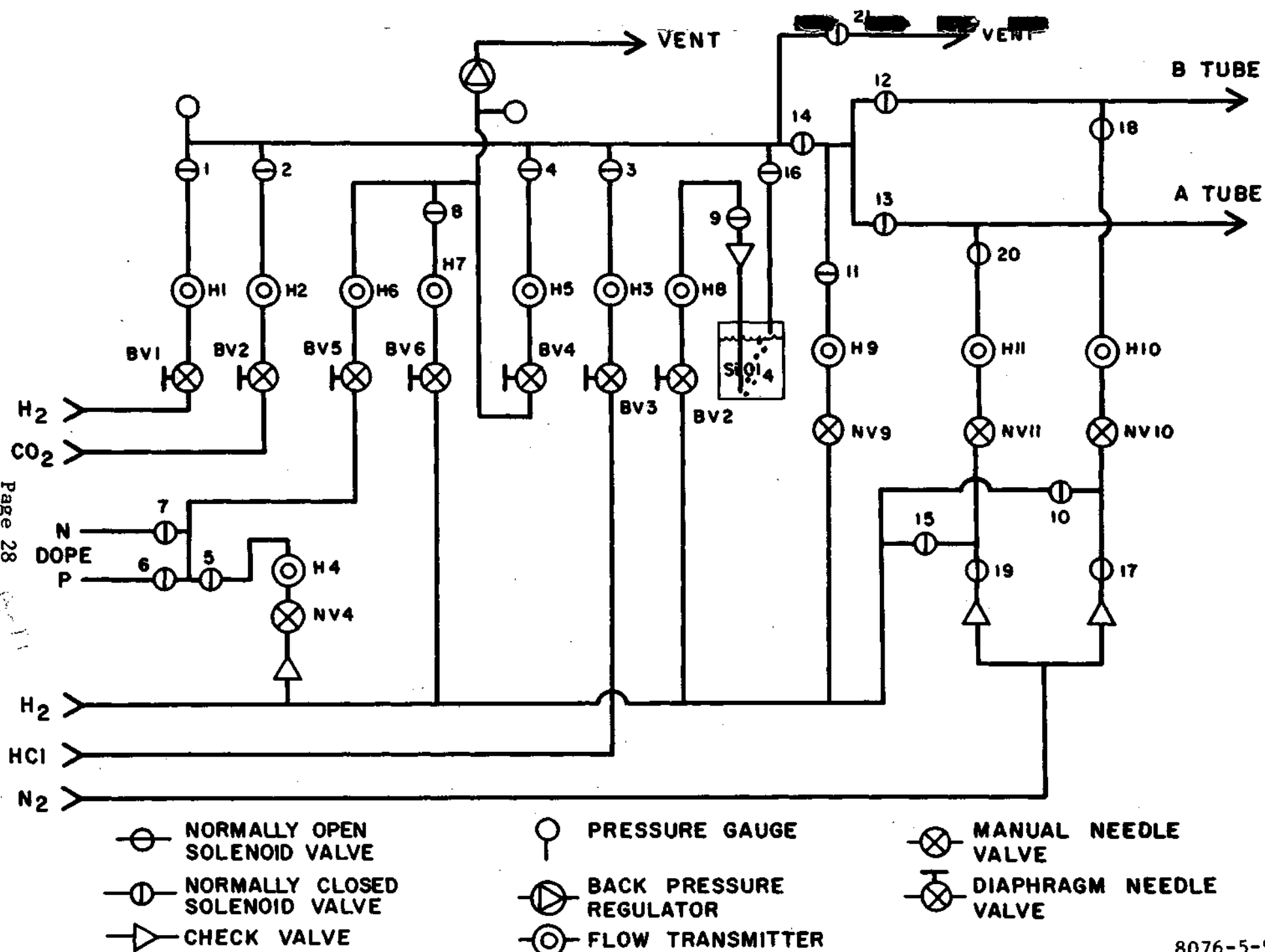
2.6   ASSEMBLY OF THE COMPOSITE CONTROL SYSTEM

The system consists of three main control functions.

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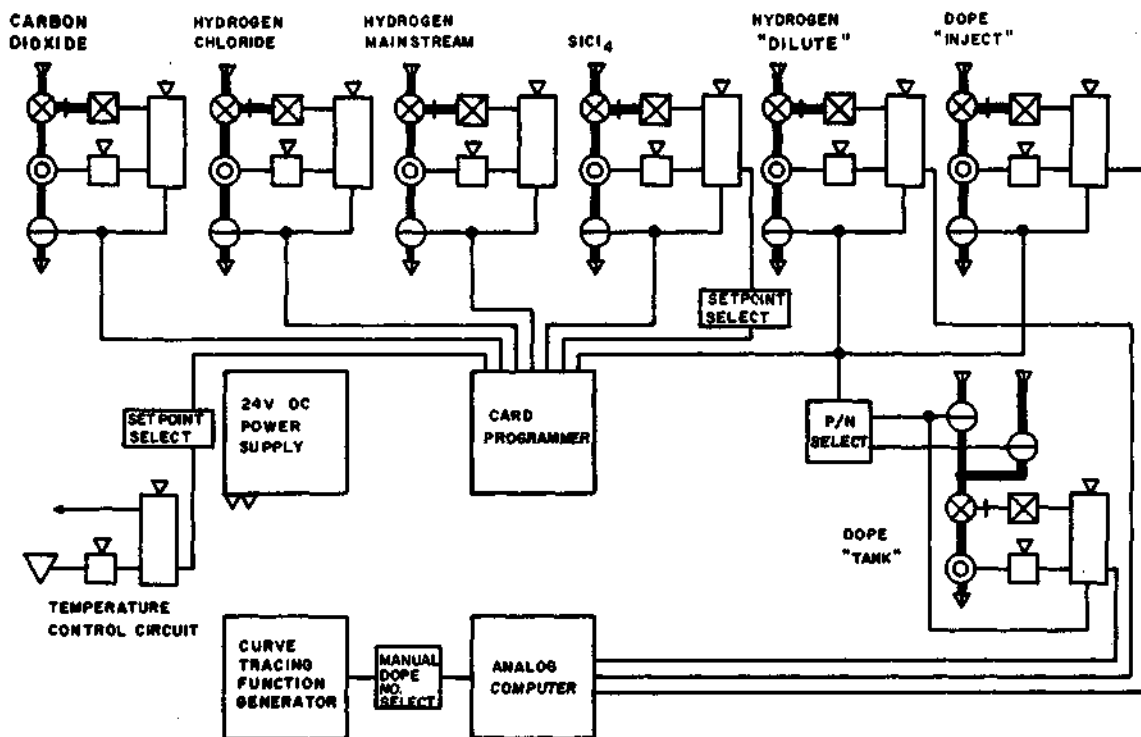Figure 7. Required Response of Analog Computation Module for Generation of Figure 4

● = Required Response for Tank and Inject Analog Module

⊠ = Points for an Exponential Function of the Form:

$$y = (1.01)(99.78)^{X/100} - 1.01$$

○ = Required Response For Dilution Analog Module

▣ = Points for an Inverse Function of the Form:

$$y = \frac{1696}{X+14.78} - 14.77$$

Dilution Set Point

Inject and Tank Set Point

INPUT PERCENT

26

7606-9-8

Figure 8. Correlation of Dope Number with Input Variable Percent

7602-9-8

DOPE NUMBER

INPUT VARIABLE,(PERCENT)

27

Figure 9. Plumbing Schematic of the Automatic Analog System

8076-5-9

CARBON DIOXIDE   HYDROGEN CHLORIDE   HYDROGEN MAINSTREAM   SICl₄   HYDROGEN "DILUTE"   DOPE "INJECT"

SETPOINT SELECT

SETPOINT SELECT   24V DC POWER SUPPLY   CARD PROGRAMMER   P/N SELECT

DOPE "TANK"

TEMPERATURE CONTROL CIRCUIT

CURVE TRACING FUNCTION GENERATOR   MANUAL DOPE NO. SELECT   ANALOG COMPUTER

NOTE: THE GAS LINES ARE DRAWN
HEAVIER TO DISTINGUISH THEM
FROM THE ELECTRICAL INTERCONNECTIONS.

GAS IN ▷ ⊙ — 0-2 mV OUT FLOW TRANSMITTER

GAS IN ▷ ⊗ — + 3-15 PSI DIAPHRAGM OPERATED NEEDLE VALVE

GAS IN ▷ ⊕ — NORMALLY CLOSED SOLENOID VALVE

24 V DC POWER
0-2 mV — ⊡ — 1-5 V MILLIVOLT AMPLIFIER

4-20 mA — ⊠ — 3-15 PSI CURRENT TO PRESSURE TRANSDUCER

24 V DC POWER
4-20 mA OUTPUT
1-5 V DC INPUT — EXTERNAL SET POINT   PROPORTIONAL CONTROLLER
SET POINT SUPPRESSION

Figure 10.   Control Schematic of the Automatic Analog System

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PROGRAMMING
CARD
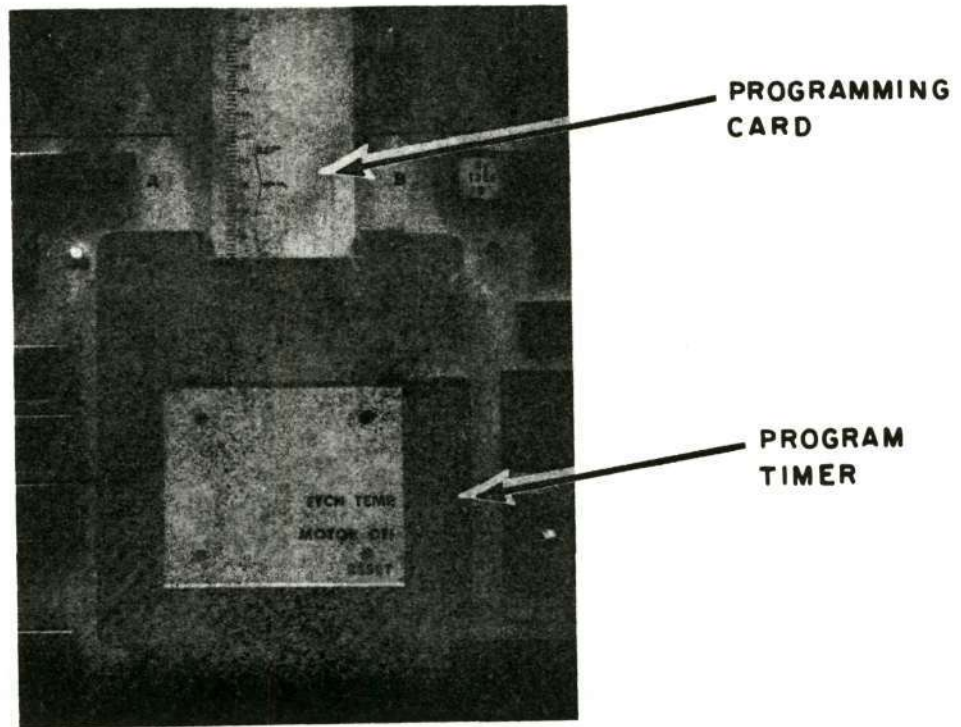
PROGRAM
TIMER

Figure 11.   12-channel Card Programmer

7604a-9-8

TABLE II

PROGRAM CONTROLLER

12 CHANNEL ASSIGNMENT

Channel	Function
1	H_2 Mainstream
2	Hold
3	Dope Purge
4	N - Dope
5	P - Dope
6	Etch
7	SiO_2
8	Step Temperature
9	Step $SiCl_4$
10	Spare
11	Recycle
12	Timer off

(1) Gas control loops.

(2) Temperature control loop.

(3) Timing of the various control functions.

2.6.1 Gas Control Loops

From Figure 9, there are seven automatic control loops and four manually controlled loops. Needle valves 2, 4, 10 and 11 are the manual loops; they do not require precision control since they are used only for purging the reactor.

Referring to Figure 2, the Veritrak receives a process voltage input from the millivolt amplifier. This signal is

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compared with the "set point," and the variation from set point is sent to the current to pressure transducer in the form of a 4 to 20 mA signal. The pressure output from the transducer opens or closes the diaphram valve, as required to deliver the proper flow through the flow transducer.

There are two basic methods for providing this set point for the Veritrak controllers. Figure 12 shows a view of a typical Veritrak controller. Notice the two buttons marked INTERNAL and EXTERNAL. In the Internal mode, the process pointer will control at the level or position of the set point pointer. This set point pointer can be adjusted with the SET POINT knob to a point between 0 and 100. When the EXTERNAL button is pushed, the controller receives its set point from the external source. As shown in Figure 10, this external set point comes from the analog computer to the tank, dilute and inject flowmeters.

2.6.2 SiCl$_4$ Set Point and Temperature Set Point

The set points for temperature and SiCl$_4$ flow are provided from two matrix pinboards. These pinboards are shown in Figure 13. They are shown schematically in Figure 14 and are functionally described below.

2.6.3 Operator Console Design

Figure 15 is an overall view of the entire epitaxial system with the operators section. A detailed explanation of the operators section and a typical run will be presented.
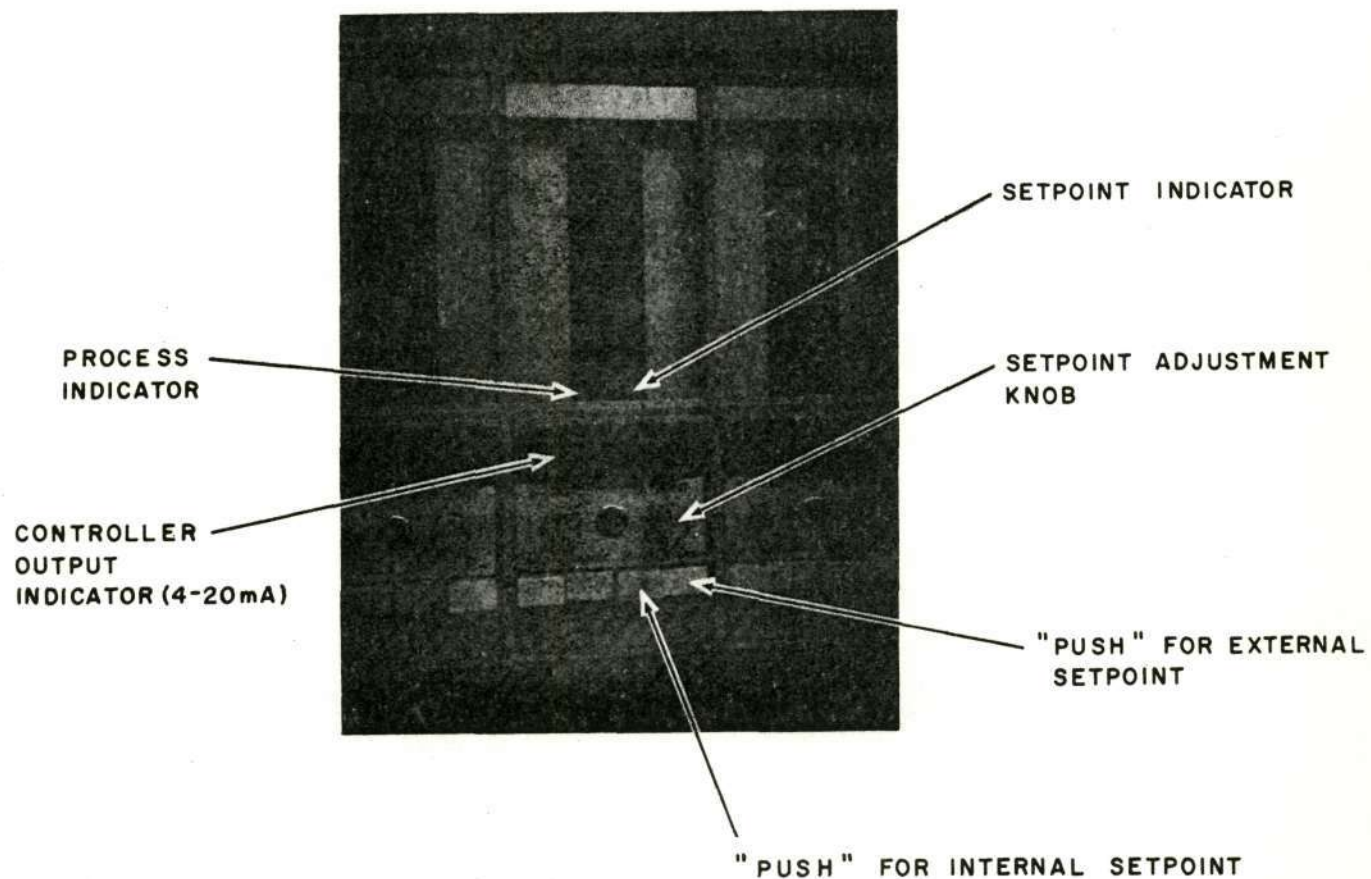
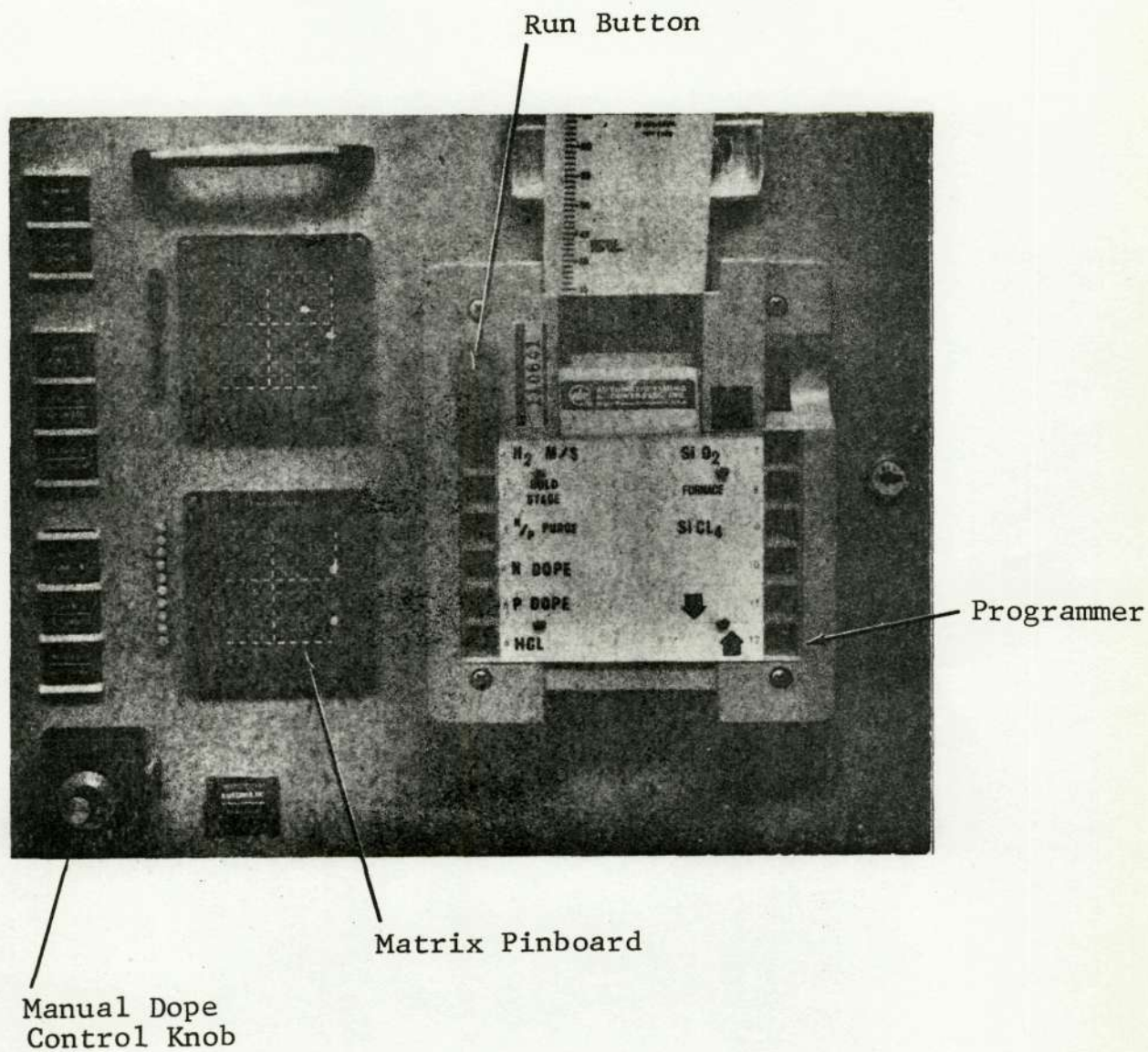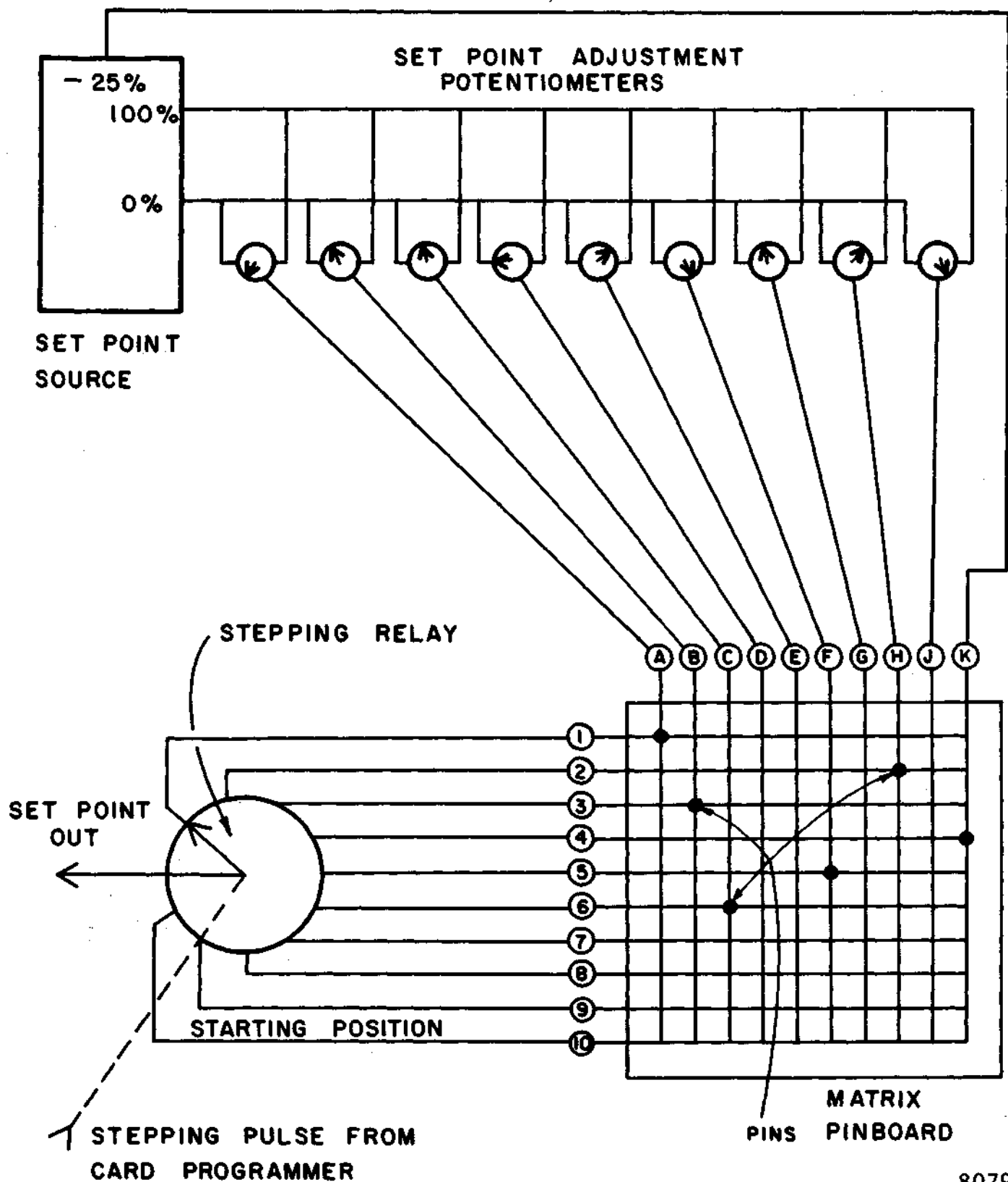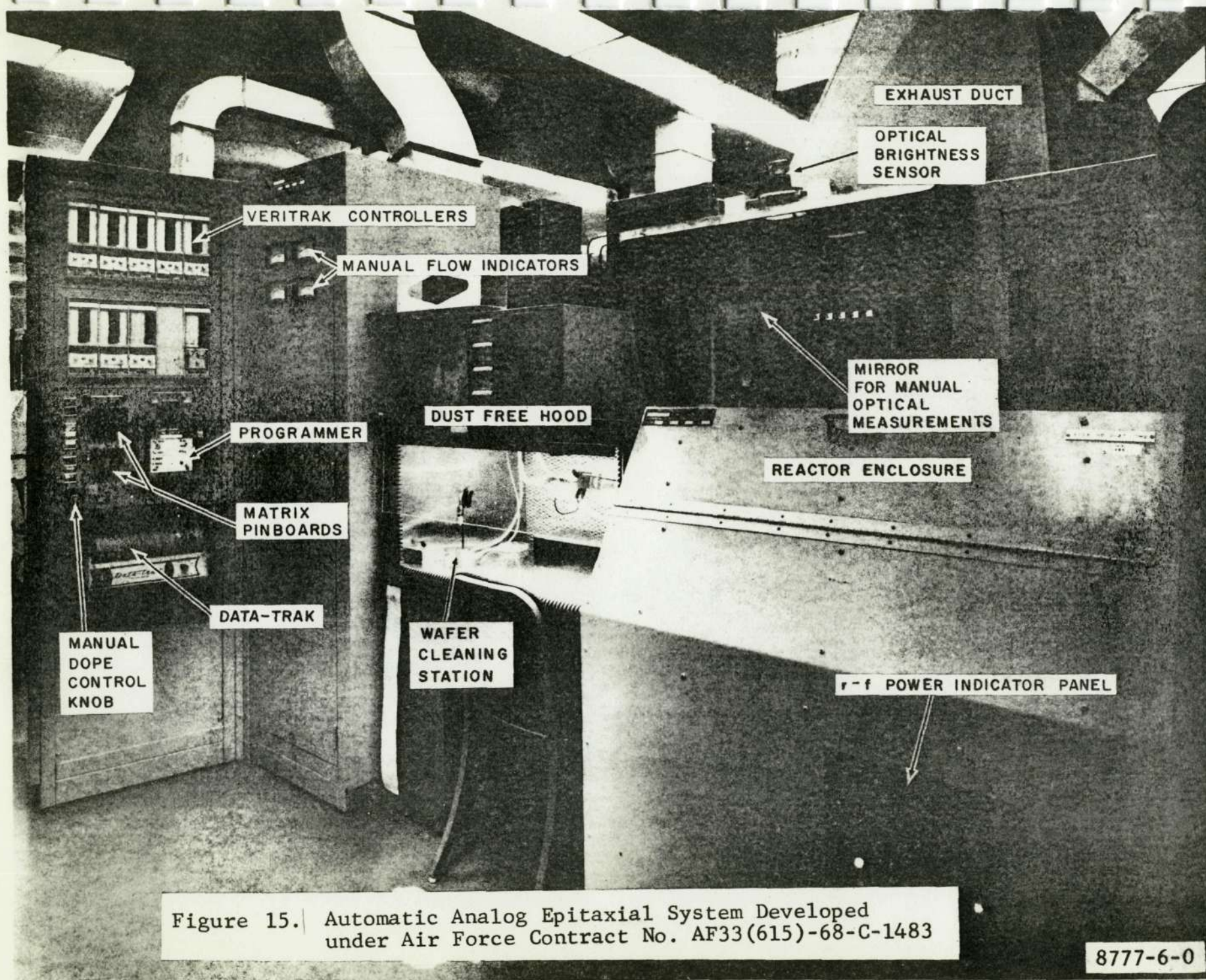Figure 12.   Front View of the Veritrak Controller

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Figure 13.   View of Operator's Panel Showing the Matrix Pinboards and the Card Programmer

8078-5-9

Figure 14.   Schematic Diagram for the Pinboard Control
System Used in Changing the Temperature and
Growth Rates

8079-5-9

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EXHAUST DUCT

OPTICAL BRIGHTNESS SENSOR

VERITRAK CONTROLLERS

MANUAL FLOW INDICATORS

MIRROR FOR MANUAL OPTICAL MEASUREMENTS

DUST FREE HOOD

PROGRAMMER

REACTOR ENCLOSURE

MATRIX PINBOARDS

DATA-TRAK

WAFER CLEANING STATION

MANUAL DOPE CONTROL KNOB

r-f POWER INDICATOR PANEL

Figure 15. Automatic Analog Epitaxial System Developed under Air Force Contract No. AF33(615)-68-C-1483

8777-6-0

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The operator console has been designed to minimize the need for operator intervention. In addition, the console is as similar in appearance as possible to other production units where the new console will be eventually located. Figure 13 is a photograph of the control panel.

The lighted switches on the left of the photograph not only initiate process functions, but they also act as annunciators for operator instruction. The POWER SWITCH turns on the main power to the electrical console. The FLAME IGNITER lamp indicates a loss of the hydrogen burn-off igniter and can be pushed for manual flame ignition. The functions of the remaining indicators on the left side of the console are outlined below.

RELOAD A - Tube "A" is in a safe condition and can be opened for loading or unloading. Indicator only.

NO OPEN A - Tube "A" is in a timed purge condition and cannot be opened safely. Indicator only.

SELECT TUBE A - This function switches the RF power to the "A" reactor. It is illuminated only when the RF is available for "A" tube.

START A - This button starts the initial nitrogen prepurge. Pushing of this button also turns on the NO OPEN A light on.

A PURGED - This light indicates completion of the nitrogen purge and start of the hydrogen purge of "A" tube. The tube remains in hydrogen purge until the "run" button on the clock timer is pushed.

B tube functions in a similar manner.

At the bottom of the panel are the dope controls. The AUTOMATIC-MANUAL button selects either "Manual" dope control by means of the dope control knob or "Automatic" dope control by means of the DATA-TRAK curve tracer.

In the center of this panel are the two matrix pinboards. These allow predetermined set points for temperature and growth rates to be automatically sequenced during the run.

Each of the pinboards contains a starting position for an associated stepping relay. For the temperature pinboard, the starting position is the "power-off" condition. For the "growth step," the starting position is a no-flow condition for the silicon tet. These functions can also be seen in Figure 14.

The card programmer has an indicator light showing the status of each tube and the growth conditions under control of the card programmer.

2.6.4   Operator Console Operation

In order to describe the operation, a typical running sequence is presented in Tables III and IV. By reference to Figures 9 and 13 of the gas control system and the operator's panel, a clear picture of the functions can be obtained. In the starting state, all solenoid valves are de-energized, which allows nitrogen to flow through normally open Valves 17, 18, 19 and 20 to Tubes A and B. This is also the condition which prevails upon loss of power to the controller. Operation indicators RELOAD A, START A, RELOAD B, START B, FLAME OUT, and POWER are one. The operator loads

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TABLE III
PROGRAMMER FUNCTIONS

Channel	Function	Solenoid Valves
1	Mainstream	1, 14 on
2	Hold	11, 21 on; 14 off
3	Dope purge	4, 5, 8 on
4	N dope	7 on
5	P dope	6 on
6	Etch	3 on
7	SiO_2	2 on
8	Step temp	
9	Step $SiCl_4$	
10	Spare	
11 ⎫ 12 ⎭	Control of card advance and reset	

TABLE IV

TIME SCHEDULE FOR GROWTH OF AN NP STRUCTURE WITH OXIDE

Elapsed Time (Minutes)	Channels Cut	Notes
0	1	Mainstream on through H1.
1	1, 2, 6, 8[A]	Mainstream is replaced by alternate (through H9) 1st temp set point selector, HCl turned on.
4	1, 6	HCl stream is passed into tube for etching process.
9	1, 2, 4, 9[B]	Mainstream is replaced by alternate HCl off, N dope on, 1st $SiCl_4$ set point selected.
9½	1, 2, 4, 8[A]	Second temp set point selected.
12½	1, 4,	N dope and $SiCl_4$ passed through tube.
17½	1, 2, 3	Replace mainstream with alternate, N dope off, purge dope lines.
18	1, 2, 5	End dope purge, P dope on.
18½	1, 5	P-dope, $SiCl_4$ pass through tube.
23½	1, 2, 9[B]	Replace the mainstream with alternate, P dope off, select 2nd $SiCl_4$ set point for oxide growth.
24	1, 2, 7, 8[A]	CO_2 on, select 3rd temp set point.
26	1, 7	CO_2 and $SiCl_4$ pass into the tube to grow SiO_2.
31	1, 2, 3, 8[A], 9[B]	Replace the mainstream with alternate, purge dope lines, select 4th temp set point (off) and 3rd $SiCl_4$ (off).
32	11	Card control channels reset the card to starting position, mainstream off.

Tube A with a set of wafers and pushes the START A indicator. This initiates a 3-minute time delay for nitrogen purging of air remaining in the tube during loading. The START A and RELOAD A indicators go out and NO OPEN A goes on. After the 3-minute interval, A PURGED goes on and Valves 15 and 19 are energized, cutting the nitrogen and allowing hydrogen to purge the nitrogen out of the tube. After loading Tube A and starting the purge, the operator may also load the push START B, which then runs through the same sequence independently. As soon as the A PURGED or B PURGED lamp goes on, the operator may select the purged tube for epitaxial growth. This is done by pushing either SELECT A or SELECT B. Assuming that both have completed the nitrogen purge, either Tube A or B can be selected. After making a selection, the card programmer is initiated by pushing the run button. If Tube A has been selected, this energizes Valves 13, 20 and 1, shutting off the purging hydrogen source and replacing it with the mainstream hydrogen. The operation at this point depends on the program which has been cut into the card being read by the card programmer. The channels on the card have the functions shown in Table III.

Figure 16 shows a structure that would be grown using the sample sequence of events in Table IV.

2.6.5   Explanation of Card Channel Functions

When Channel 1 is sensed on, a spark igniter goes on for 30 seconds to ensure that hydrogen passing out of the tube is burned before going out the vent. When a flame is sensed, the FLAME indicator goes off.

All proportional controllers (except temperature), are connected to the solenoid valves in their gas line so that a zero set point is impressed when the valves are closed. This prevents
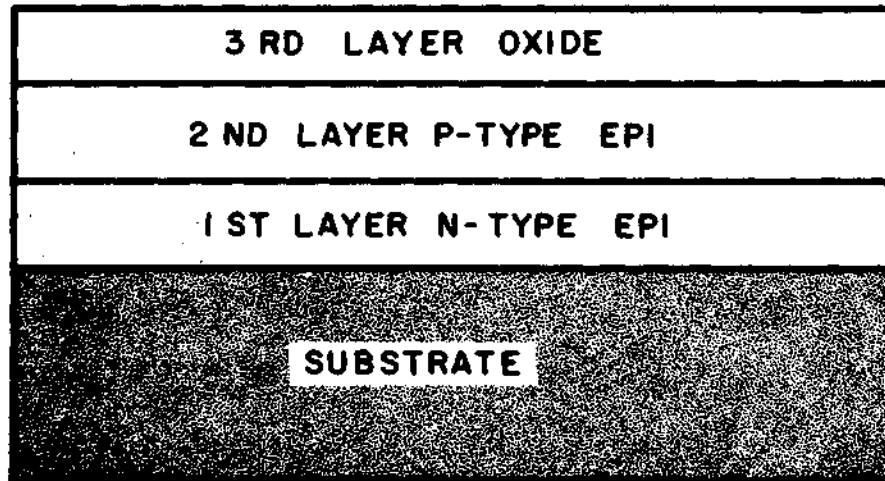
41

Figure 16. Typical Epitaxial Structure which Would be
Grown Using the Schedule Listed in Table IV

the control output from going to 100 percent during off periods, and allows a soft start when the gas is turned on. Channel 8, with an A superscript, operates through the temperature matrix pinboard. This pinboard is shown on the panel in Figure 13. Figure 14 is a pictorial schematic of the pinboard arrangement. Only a momentary contact is sensed by the programmer from Channel 8. This causes a stepping relay to advance on position; maximum of 10 steps before repetition. These positions are wired through the pinboard to select a set point for the temperature controller. The tenth position is a rest point at which the RF generator is switched off.

Channel 9 with a B superscript operates similarly to Channel 8 through the $SiCl_4$ matrix pinboard, but controls the $SiCl_4$ solenoid valves instead of the RF generator. Valves 9 and 16 are energized whenever the associated stepping relay is off its rest position (10), and a normal set point (other than Column K) is selected. On both pinboards Column K is a -25 percent set point. In the case of the $SiCl_4$ control loop, this is interpreted as an off command and Valves 9 and 16 are closed. In the case of the temperature control loop, it is interpreted as a zero set point.

Channel 3, in addition to opening Valves 4, 5, and 8, also activates a relay which replaces the set points of the controller attached to flowmeters H5, H6, and H7, and control valves BV5, BV6, and BV7 with a 100-percent valve, thereby assuring that all lines are fully open for thorough purging of gases left from the previous operation.

When the program card reached the end of the program and returns to its starting position, all control channels are de-energized; both stepping relays (temperature and $SiCl_4$) are reset

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to their starting position, and a timer starts a cool-down hydrogen purge by de-energizing Valves 13 and 20 (Tube A) or Valves 12 and 18 (Tube B). After 15 minutes Valves 15 and 19 (Tube A) or Valves 10 and 17 (Tube B) are de-energized, allowing nitrogen gas to pass into the tube to purge out hydrogen. After an additional 3 minutes, these timers stop and RELOAD A, START A or START B, RELOAD B come on again to bring the system back to its starting configuration. The pre-purge and post-purge times are separate for Tubes A and B, allowing independent operation and reloading while the alternate tube (A or B) is being controlled by the card programmer.

Set points for the mainstream, oxygen, and HCl etch are obtained within their associated controllers shown in Figure 17, since they are fixed values and are rarely changed. The temperature and $SiCl_4$ set points are selected from a range of 10 fixed values through their matrix pinboards as described above. The set points for tank (H6), dilute (H7) and inject (H5) are indirectly derived either from a manual resistivity control, Figure 13, or the DATA-TRAK shown in Figure 18. A switch selects the manual or automatic mode. In the automatic mode, the chart drive of the DATA-TRAK Curve Tracer starts when two conditions are fulfilled.

(1) Either N or P dope, Valve 6 or 7, is on,
(2) Hold (Channel 2) is off.

These are the conditions when a doped growth process is taking place. The signal from the selected one of these sources is processed by the two function generators to produce set points such that the resistivity of the grown material is proportional to the logarithm of the input signal. When the growth process stops, the DATA-TRAK chart drive continues for a short time until a "stop" switch is tripped on the drum periphery.
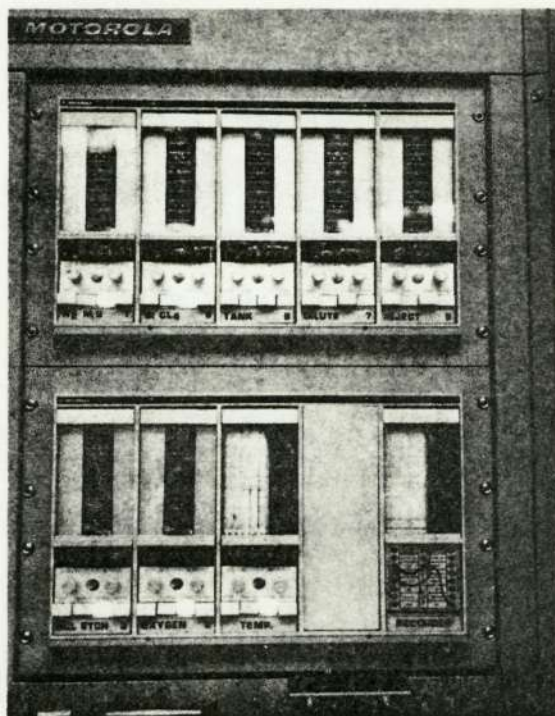
44

Figure 17. Control Panel Showing the Proportional Controllers
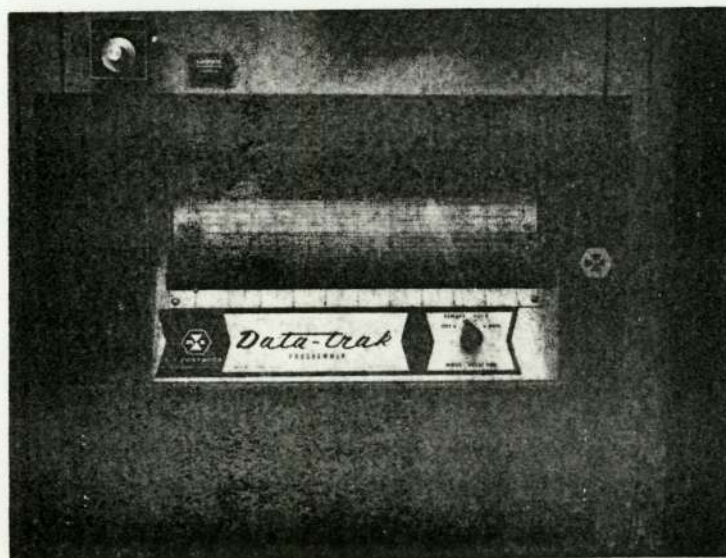for the Process Gases and Temperature

Figure 18. DATA-TRAK Programmer for Automatic Programming
of the Resistivity Set Point

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2.7   MANUAL PANEL OPERATION

        In addition to the automatic control mode of operation,
all functions (except pre-purge and post-purge) may be controlled
manually. By pulling out the control panel a short distance, a
second horizontal manual control panel is exposed as in Figure 19.
One switch selects whether the system is to be operated in the
manual or automatic mode. In the manual mode, a separate switch
and indicator lamp is connected to each control loop. Four switches
are also provided to stop operation of the RF generator, stop the
DATA-TRAK chart drive, manually step the temperature and manually
step the $SiCl_4$ set point select relays. Other items found on this
panel are power switches and fuses for the various components of
the system. These are in use for both automatic and manual operation.

        From Figure 9, four flows are manually controlled: dope
purge (NV4 and H4), alternate mainstream (NV9 and H9), Purge A (NV11
and H11), and Purge B(NV10 and H10). These have separate flow indi-
cators as shown in Figure 20.

2.7.1   Calibration of the Flow Sensors

        The mass flow meters are used in two modes of operation.
In the first mode, the flow meter is used for a flow indicator only.
These meters will be used in the nitrogen and hydrogen purge lines.
These are relatively noncritical flows and need not be controlled
with a closed loop system. Flow in these loops will be monitored
using a direct reading millivolt meter. These gas lines can be
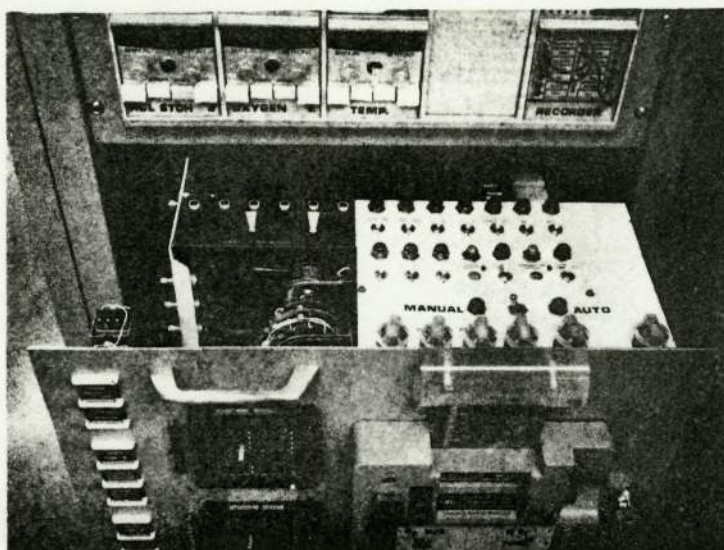located in Figure 9.

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Figure 19. Manual Control Section Mounted on the Reverse
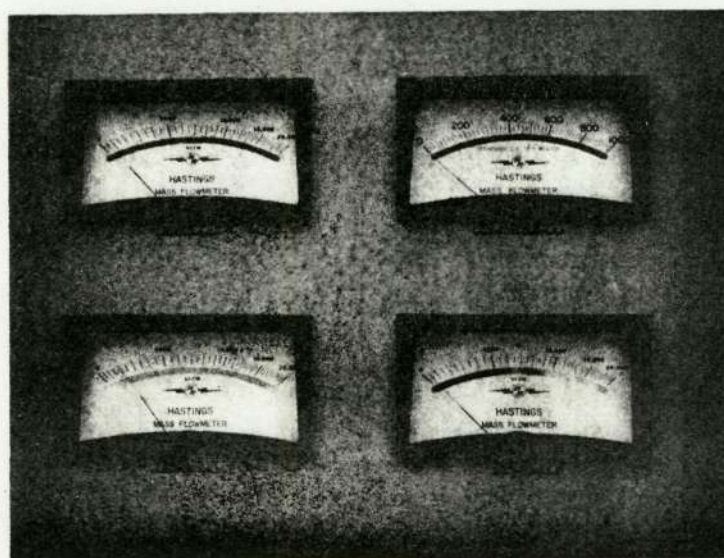Side of the Operator's Control Panel

Figure 20. Flow Indicators for the Manually Controlled Flows

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In the second mode, the mass flow meters are used as a sensor for closed loop control. In this use, the output of the sensor goes to a millivolt amplifier and from there to the analog controller. Figures 9 and 10 show these components.

To give the proper range and linearity to the flow sensors, the amount of gas bypass through the flow meter was adjusted by enlarging or decreasing the size of the bypass port. This was largely a trial-and-error process. The volumetric flow meter shown in Figure 3 was used for this calibration and adjustment. The placement of the volumetric flow meter for calibration purposes is shown in Figure 2. This modification would normally be done by the factory and the meters would be received in correct calibration.

2.8   TESTING OF THE COMPLETED CONSOLE

The basic system components are divided into four areas:

(1) The gas flow control loops
(2) Temperature control loop
(3) Resistivity control module and DATA-TRAK Curve Tracer
(4) Temperature and $SiCl_4$ matrix pinboard set points.

2.8.1   Evaluation of Growth and Etch Rates

The test procedure consisted of actual growth of silicon epitaxial films under various conditions. In each growth run, five 2-inch wafers (12 to 15 ohm-cm, p-type) were used. They were arranged in the furnace as shown in Figure 21. In each run, only the three middle wafers were evaluated; that is, B, C, and D.

To obtain preliminary data as quickly as possible to evaluate growth rates and etch rates, the runs were made simultaneously according to the schedule in Table V. Each run consisted of 10 minutes etch at 1200° and 20 minutes growth at 1100°C.
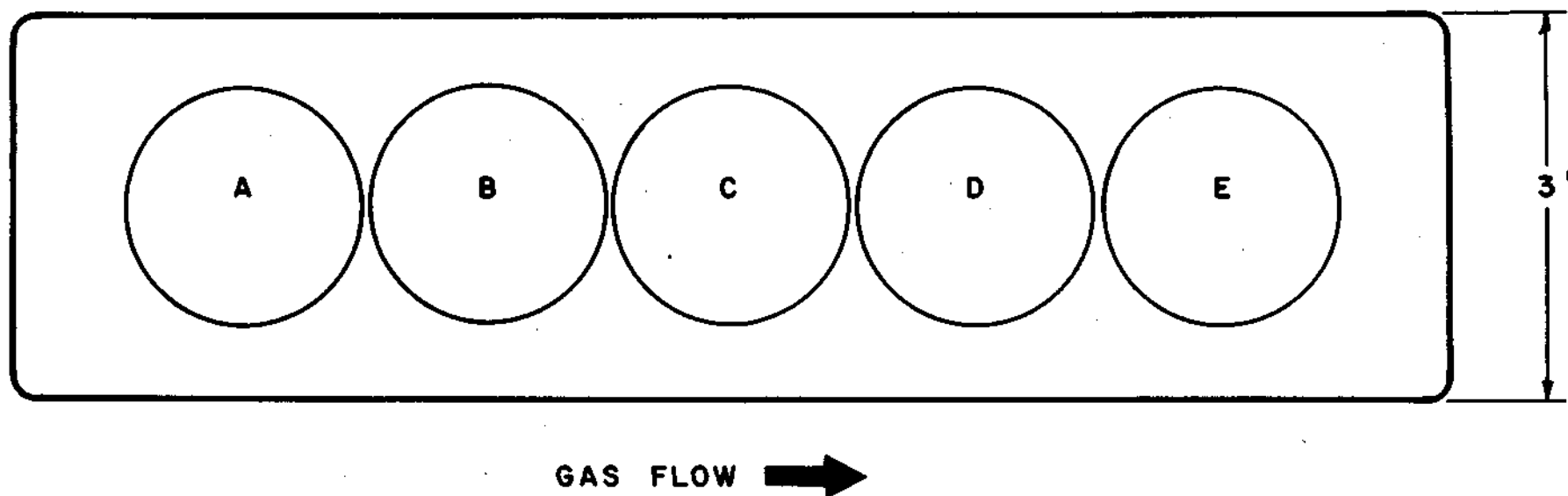
Figure 21. Wafer Configuration for Loading the Analog Epitaxial System

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TABLE V

SCHEDULE OF GROWTH AND ETCH RATE EVALUATION

Run No.	SiCl$_4$ Set Point Percent	HCl Set Point Percent
1	0	100
2	10	90
3	20	80
4	30	70
5	40	60
6	50	50
7	60	40
8	70	30
9	80	20
10	90	10
11	100	0

These wafers were weighed before and after the run to
obtain the net thickness change.   They were also subjected to a
bevel and stain thickness test to obtain an independent measure
of growth.   The etch thickness loss was obtained by difference.
Figure 22 presents a graph of the results.   Hydrogen flow was held
constant at 40 liters/minute.   As might be expected, the etch rates
displayed considerable scatter, because of errors compounded in this
method of rate determination of difference.

The temperature control has operated satisfactorily at
all times so far.   Since this is only a duplication of the temper-
ature controls already in use on previously built epitaxial systems,
no detailed data on its performance is included.   Consistent control
and reproducibility of set point to within ±0.27 percent (±3° at
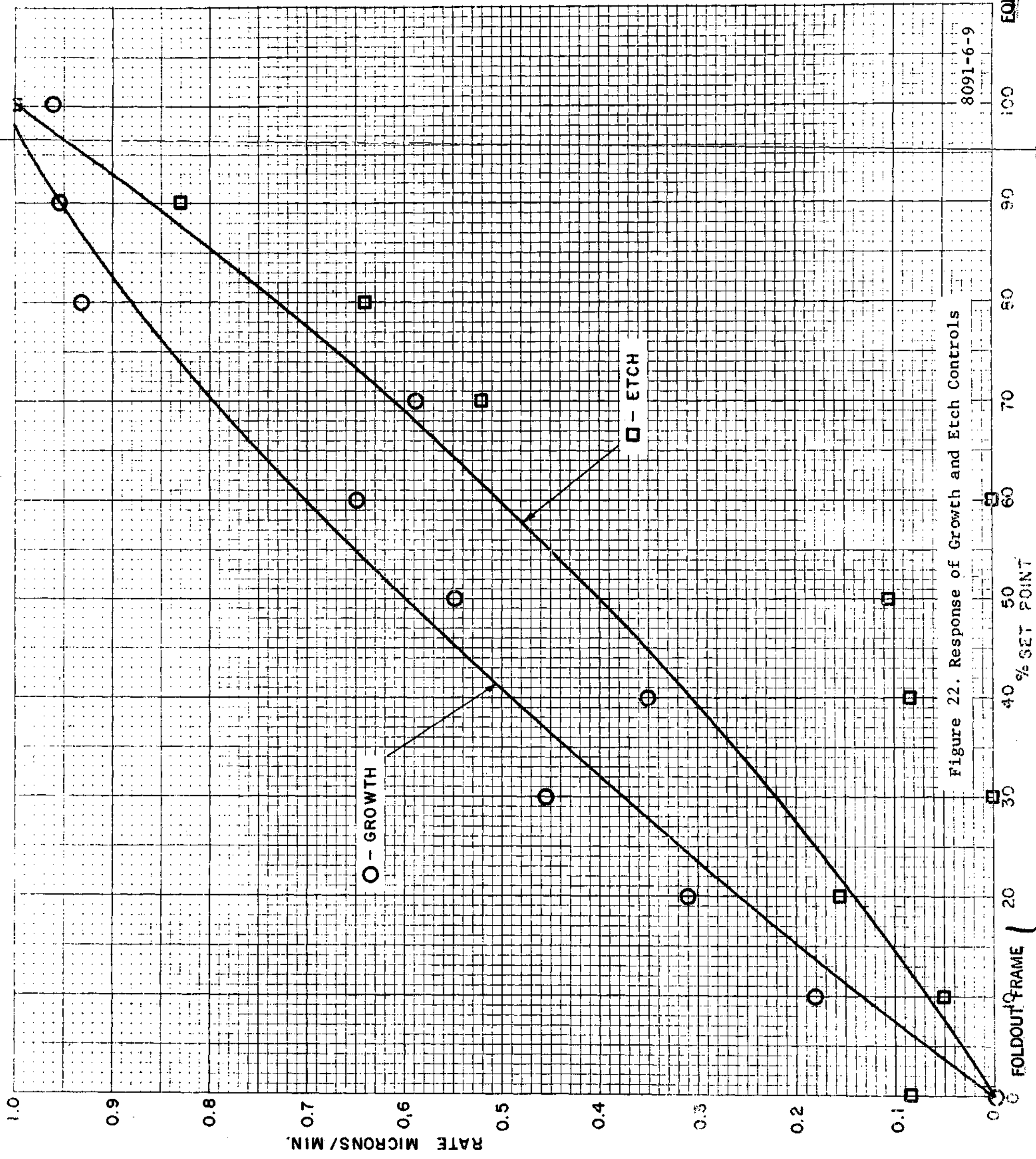1100°C) has been experienced.

Figure 22. Response of Growth and Etch Controls

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○ — GROWTH

□ — ETCH

% SET POINT

RATE MICRONS/MIN.

The matrix pinboard selection of temperature and $SiCl_4$ flow rate set points have also operated very satisfactorily since the system was installed.

2.8.2   Resistivity Control

The most complex element in the automatic system is the method of dope control. Figure 23 is a block diagram of its basic configuration along with plots of the set points which it generates in response to the resistivity control input. Function generators used in this doping control method contain adjustments which allow changes in the shape of the set point output curves. This permits an adjustment of the shape of the resultant resistivity versus input (from the resistivity potentiometer). Figure 24 illustrates this capability as well as the performance of the complete doping control module.

Initially the system was installed with a 100-parts-per-million doping gas supply. Eleven runs and the curve labeled "100 PPM" is the result of this series without adjustment of the function generators. The doping control was designed to result in a logarithmic relationship between grown silicon resistivity and the input variable, (percent of resistivity potentiometer setting). It was apparent that two corrections were needed:

(1)   Use of a higher concentration doping source to obtain a lower minimum resistivity.

(2)   Adjustment of the function generators to obtain a more linear semi-logarithmic response.

The curve labeled "1000 PPM" is the result of the second series of runs made after these corrections were accomplished.
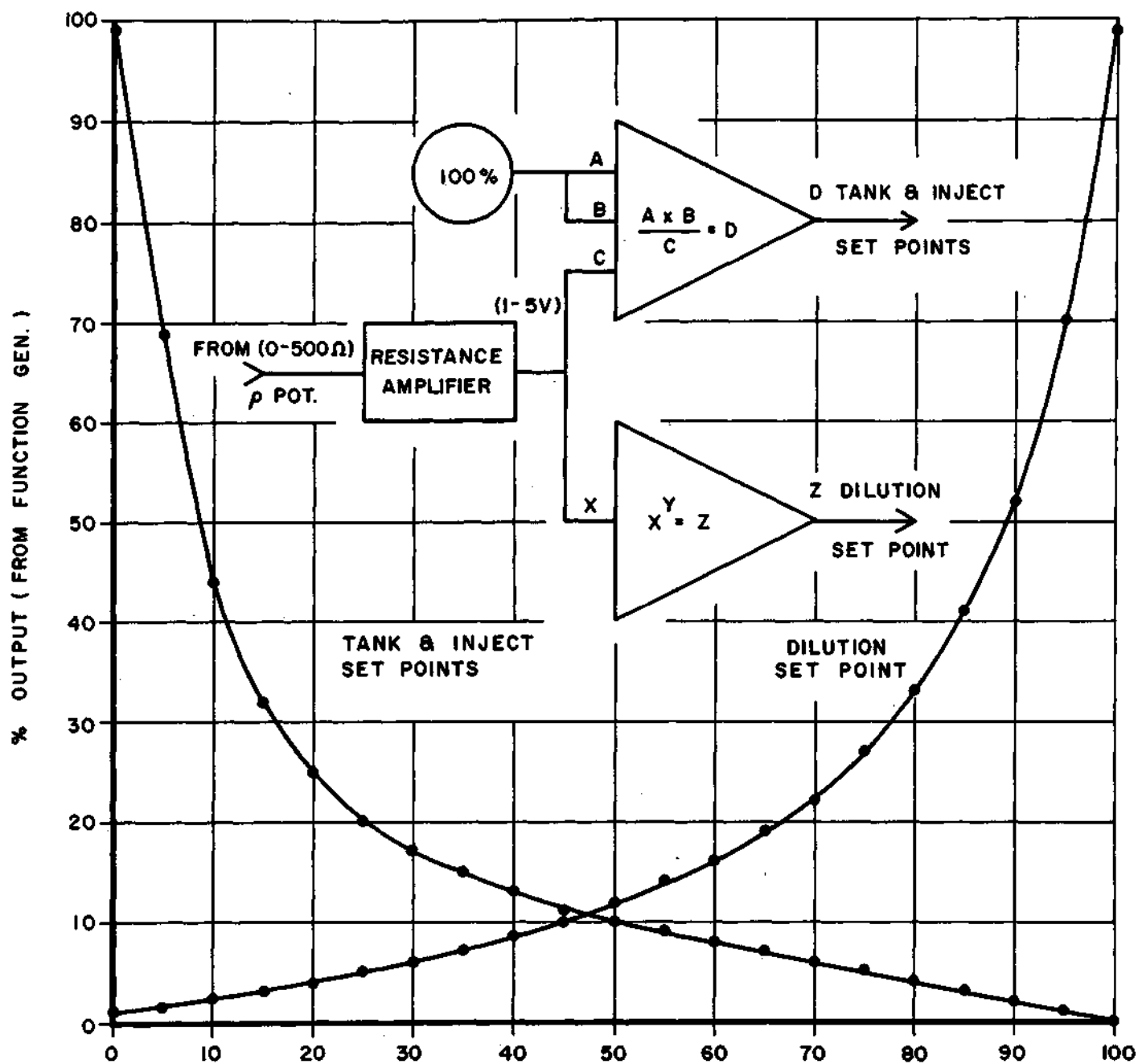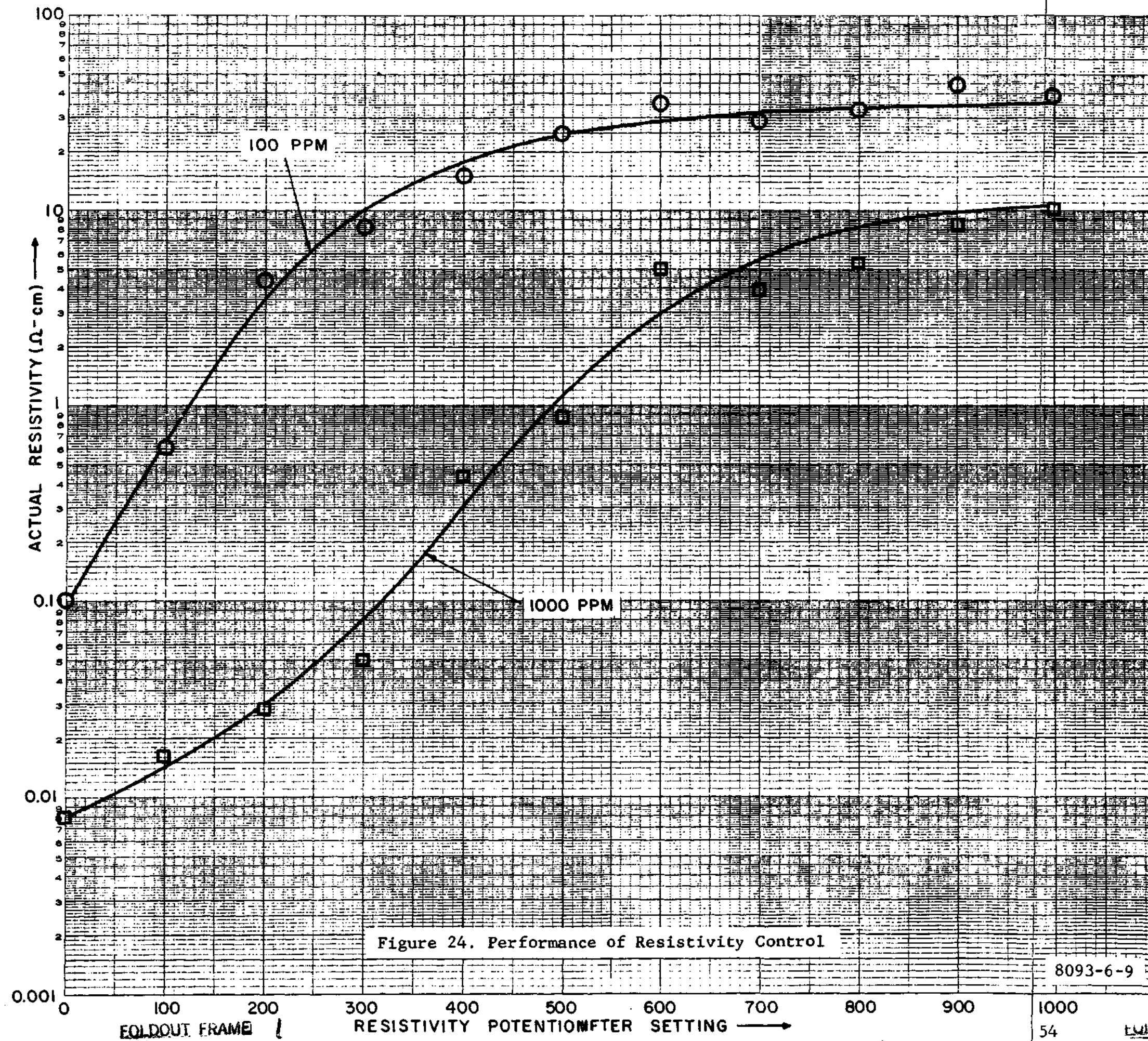
52

Figure 23. Resistivity Control Function
Generator Schematic

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Figure 24. Performance of Resistivity Control

100 PPM

1000 PPM

ACTUAL RESISTIVITY (Ω - cm) ⟶

RESISTIVITY POTENTIOMETER SETTING ⟶

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Three things are apparent in this curve:

(1) An upper limit of resistivity is being approached, which is probably a result of doping from sources other than the doping gas and therefore, not completely under direct control.

(2) The plot is not linear because of imperfections in the doping control function generators, and also because resistivity of silicon is not a linear function of impurity concentration.

(3) There is a certain amount of scatter in the data obtained because of flow meter drift and other noncontrolled factors.,

2.9   STUDIES ON SYSTEM REPEATABILITY

A series of studies on run-to-run repeatability were made at 1000°C. Figure 25 illustrates the dependence of the $SiCl_4$ flow on temperature to attain a constant growth rate. The data were generated by making several runs, each shown as a datum point. The layers were grown for 20 minutes and were 5 microns thick, giving a 0.25-micron-per-minute growth rate. From Figure 25, a ±5°C variation in wafer-to-wafer temperature at 1000° gives rise to a ±55 cc flow difference in order to maintain the 0.25 micron-per-minute growth rate. At 1100°C the flow difference is only 6 cc/minute per 5°C. The growth temperature at these low temperatures of 1000°C is, therefore, very critical. From a production standpoint, a 5°C temperature variation down the epitaxial boat is about the practical limit.
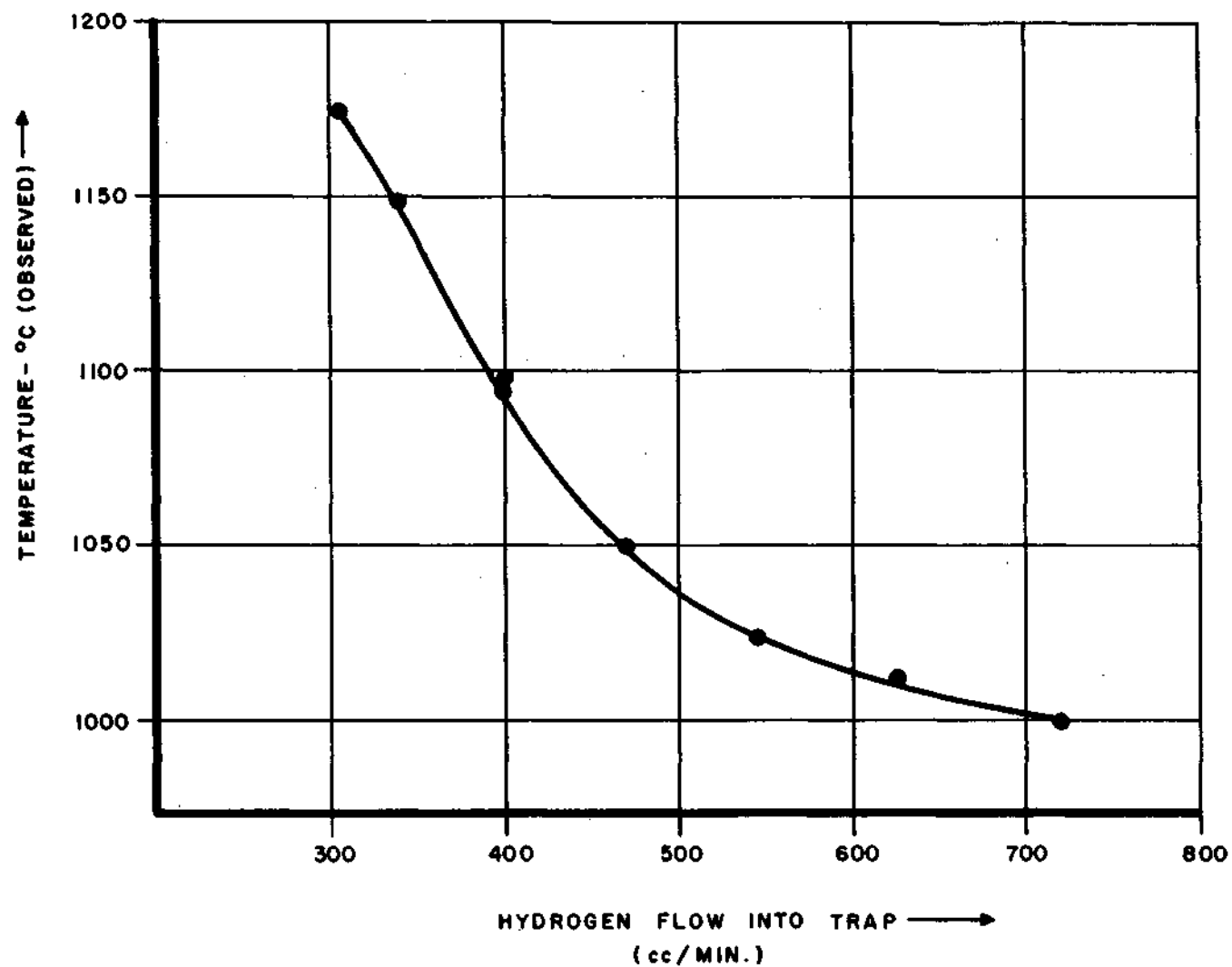
55

Figure 25. Temperature vs SiCl$_4$ Flow for
0.25-Micron per Minute Growth Rate

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This heavy dependence of growth rate on temperature is further illustrated by Table VI. The table presents the data for two epitaxial runs made before and after a careful furnace temperature correction.

TABLE VI

RUN AT 1000°C BEFORE AND AFTER FURNACE TEMPERATURE PROFILE
SUBSTRATE - 0.003 Ω-cm, n-TYPE
2" DIAMETER. 5 WAFERS PER BOAT LOAD

	Before Temperature Correction Run 1/29/70					After Temperature Correction Run 1/30/70				
Wafer Location	1	2	3	4	5	1	2	3	4	5
Thickness (microns)	8.0	9.0	10.6	12.2	12.5	11.6	11.1	10.4	10.5	10.1
Resistivity (Ω-cm)	0.22	0.23	0.29	0.34	0.34	0.25	0.25	0.23	0.23	0.23
Wafer Temp (°C)	985	990	1000	1110	1110	1000	995	1000	1000	995

The thickness variation before the temperature correction was ±20 percent; after correct temperature profiling, the thickness variation has fallen to ±7 percent.

The ability of the furnace to control flows and temperature was further characterized by a series of nine runs--three runs on three separate days.

Three runs were made on February 2, 1970. The second set was made on February 3, 1970, and still another set was made on February 5, 1970. The run conditions and results are presented in Table VII.

TABLE VII

TABULATION OF THREE-DAY SERIES TO DETERMINE
RUN-TO-RUN REPEATABILITY

Three Day Thickness Average = 10.7 u
Three Day Resistivity Average = 0.31 Ω-cm

Wafer Position									Run Average	Deviation from 3 Day Average(%)
e 2/2/70	1	2	3	4	5	6	7	8		
·t Run										
Thickness	11.0	10.0	9.3	9.7	10.5	11.3	12.3	11.8	10.7	0% (+1.9%)
esistivity	0.31	0.31	0.30	0.27	0.28	0.28	0.31	0.31	0.30	-3%
d Run										
Thickness	13.2	13.0	12.5	12.3	12.5	12.8	12.1	12.9	12.6	+17%
esistivity	0.33	0.36	0.36	0.36	0.36	0.34	0.36	0.39	0.36	+16%
.u Run										
Thickness	10.2	10.5	10.6	10.0	10.9	11.5	11.3	11.2	10.7	0% (+1.9)
esistivity	0.32	0.30	0.30	0.30	0.28	0.30	0.30	0.30	0.30	-3%
:te 2/3/70										
Run										
hickness	9.6	9.8	10.9	10.5	10.5	10.1	10.9	11.1	10.4	-2.8%(-1%)
Resistivity	0.35	0.32	0.32	0.29	0.29	0.28	0.35	0.35	0.32	+3%
. Run										
hickness	10.5	10.2	10.5	10.4	10.5	10.8	10.8	11.3	10.6	-0.9%(+1)
Resistivity	0.28	0.28	0.32	0.30	0.32	0.35	0.35	0.37	0.32	+3%
· ! Run										
hickness	10.5	10.4	10.2	10.4	10.1	10.1	9.9	10.9	10.3	-3.7%(-1.9)
Resistivity	0.33	0.34	0.30	0.29	0.28	0.28	0.30	0.32	0.30	-3%
:e 2/5/70										
·t Run										
Thickness	10.7	10.0	10.0	9.9	10.6	9.9	10.9		10.3	-3.7%(-1.9)
esistivity	0.36	0.36	0.30	0.30	0.30	0.30	0.31		0.32	+3%
id Run										
Thickness	10.9	10.4	9.5	10.0	10.2	10.0	10.0		10.1	-5.6%(-3.8)
esistivity	0.35	0.31	0.30	0.30	0.30	0.29	0.28		0.30	-3%
:d Run										
Thickness	9.4	9.4	9.2	10.0	9.8	12.6	13.5		10.5	-1.9% (0)
esistivity	0.26	0.23	0.25	0.25	0.23	0.25	0.28		0.25	-23%

ote: Substrate is 0.01 ohm-cm, n-type, 1.5-inch diameter; 5-micron etch removal; 1000°C grow temperature. 30-minute grow time. Layer is n-type, phosphorous doped. Numbers in parenthesis indicate the deviation ignoring Run 2 on 2/2/70 and Run 3 on 2/5/70.

Examining all nine runs, the automatic system is as good as a manual system. This is significant since no operator attention was required. With the exception of the second run on February 2, 1970, and the third run on February 5, 1970, the thickness repeatability is within ±6 percent of the average and resistivity is within ±3 percent of the average.

The second run on February 2, 1970 appears to be a malfunction in the temperature control circuit or silicon tet flow. The variation is too great for normal error as compared to the rest of the runs.

The third run on February 5, 1970, indicates a temperature variation down the boat caused by loss of a good temperature profile from wafer to wafer. The center wafer is very close to the three-day average. The loss of good profile is not an electrical process variable but rather inadvertent disturbance of the RF coil.

Disregarding the suspect data from the second run on February 2, 1970, the thickness variation is ±3.8 percent from day to day. This rivals the best manual control. Based on the results of these runs, a variation of ±5 percent in thickness and resistivity from run to run is easily attainable on this system. A level of ±2½ percent appears probable as instrumentation is improved and the causes of the variation of the two poor runs are isolated.

Of course, the resistivity tolerance will not necessarily hold for other resistivity ranges, but the thickness variation should be applicable for all films from 2 to 30 microns in thickness.

Higher resistivity ranges would pose a more difficult case from run-to-run resistivity variation. This loss of control at resistivities greater than 5-ohm-cm is partly due to the enhanced effect of the system "background" and substrate interaction.

The immediate purpose is to show the variation due primarily to dope flow control instrumentation. The range of 0.25 to 0.35 ohm-cm is a common range for integrated circuits manufacture.

APPENDIX C

INDUSTRIAL MODULAR SYSTEMS, INC.

IMS DIFFUSION PUSHER TRANSPORT

Description

Mechanization of the diffusion process has been achieved by making it a continuous rather than a batch process, and by passing the wafers through the furnace tube, in one end and out at the other. The Continuous Diffusion Pusher System can be understood from Figure 1, which is a diagram of a plan view.

Figure 1
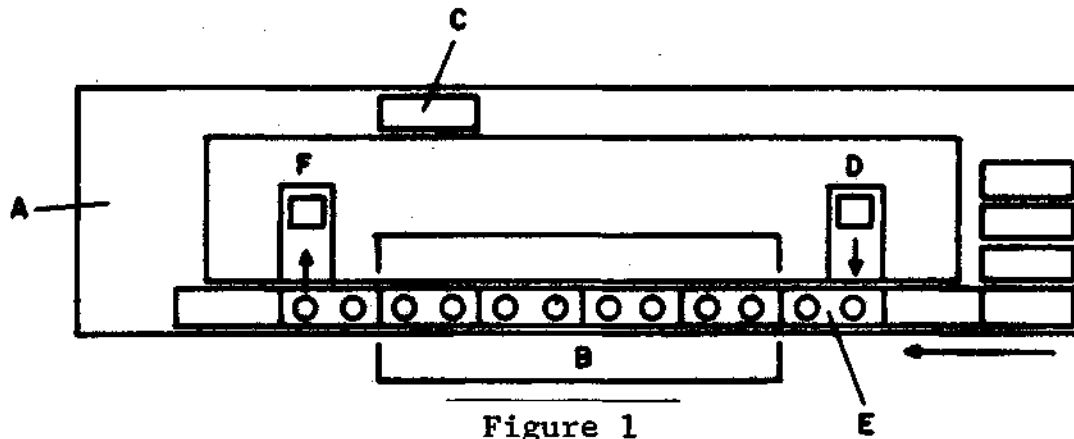
This system is a closed racetrack for passing boats through the furnace B and recirculating them around the outside C.

Wafers are unloaded from a carrier at D onto flat quartz boats E, which are passed in a continuous line through the furnace tube. On emerging at the far end of the tube the wafers are re-loaded into a carrier F. The quartz boats are returned to the front of the furnace for recycling along Track A. While the quartz boats are carried outside the furnace on an air bearing Track A, inside the furnace, they slide along guide rails as shown in Figure 2(a).

Figure 2
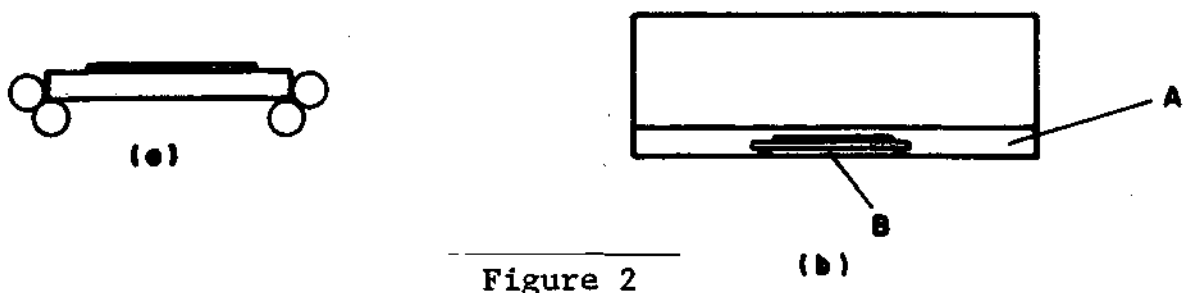
These rails are made from quartz rods welded to the furnace tube and to each other, and serve to elevate the boats from the bottom of the tube to reduce friction, and to keep the boats confined laterally. The motive power propelling the boats in the furnace is a mechanical pusher, which can vary the speed through the furnace between zero and 4.5 inches per minute.

The furnace tube has a rectangular cross section (as shown in Figure 2(b)) of dimensions approximately 3 x 1 inches. Quartz plates are held against the ground ends of the tube, closing them except for a slot A at the bottom to allow passage of the boats B.

Advantages

The advantages of this system are very considerable. Since the wafers pass down the length of the furnace tube, every wafer sees an identical integrated thermal and gas environment, which makes fluctuations in temperature and gas composition concentration along the furnace unimportant. This gives diffusion profiles of far greater uniformity that can be obtained by conventional batch processes. Also, since the process is continuous there is no recovery time between runs, which results in improved thruput. Also, by raising the temperature of the end zones of the furnace an additional ten inches of furnace can be used, increasing thruput (Figure 3 (b)).

Applications

The IMS Diffusion Pusher Furnace Transport is being used very successfully both for Continuous Diffusion of silicon wafers and for Continuous Glass Deposition on silicon wafers.

Diffusion

Boron Doping

The Continuous Diffusion System is being used for Boron diffusion at temperatures between 1000-1100°C and can be used up to 1150°C. Boron diffusion is used to define resistor and base areas in integrated circuits and the uniformity and reproducibility of this step is crucial to obtaining high yields.

Boron diffusion has been performed using both Boron Tribromide gas and Boron Nitride slabs as doping sources.

Boron Tribromide

The furnace tube configuration is shown in Figure 3.
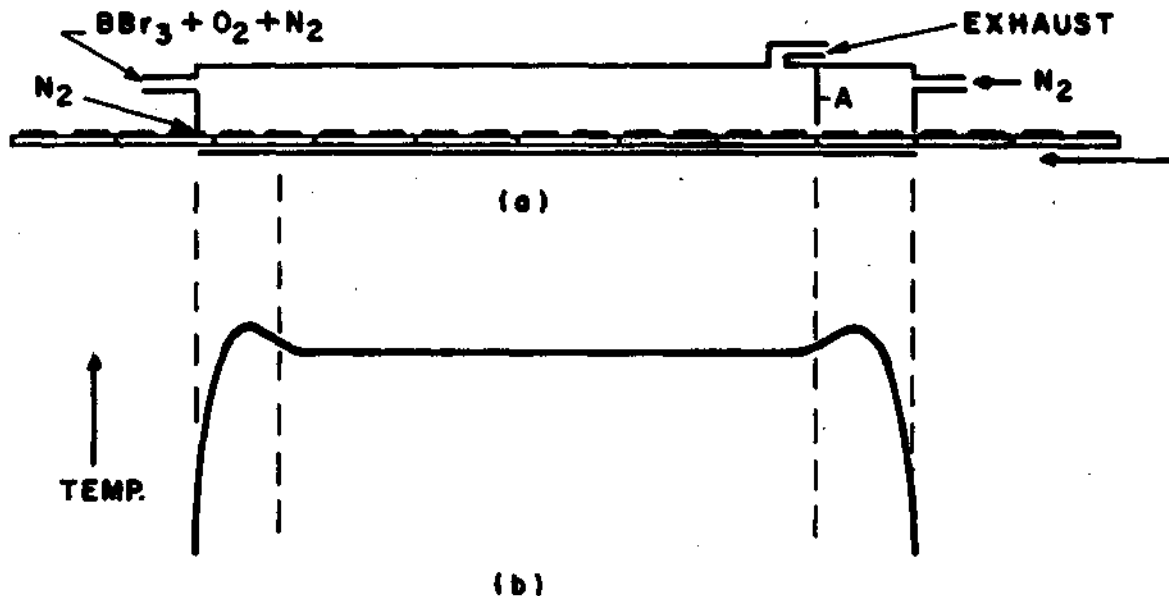
Figure 3

A rectangular section tube is closed at both ends by quartz plates held against the ground ends of the tube. A slot is left at the bottom to allow passage of the flat boats and wafers (Figure 2 (b)). The end of the tube at which the boats enter also contains a bulkhead A four inches in from the end. This provides a buffer zone of nitrogen to isolate the doped gases in the center of the furnace. Doped gases are also exhausted from this end.

At the other end of the furnace at which the boats emerge, a broad nitrogen jet is directed at the exit slot to prevent doped gases from leaking out of the tube. The doped gases are introduced into the tube at this end.

In order to make use of a longer section of the tube than the usually available 22 inch flat zone, the end zones of the furnace are raised as shown in Figure 3 (b). This serves to increase the useful length, and hence, the thruput of the furnace. This is because the long term temperature stability, and not the temperature profile is the important parameter when continuous diffusion is used. For doping levels of $150\Omega/cm-2$ a maximum variation from wafer to wafer of $\pm 5\%$ can be obtained with $\pm 1/2\%$ over a wafer.
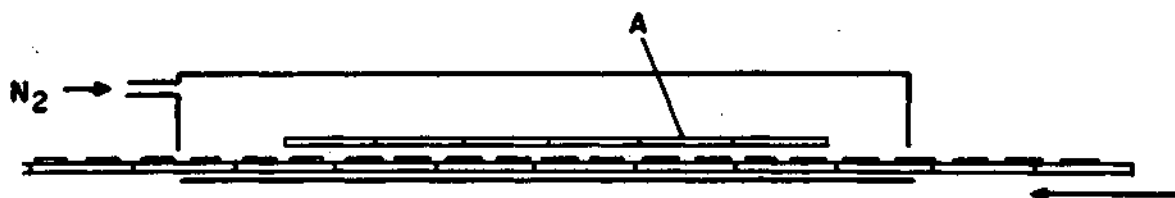
Figure 4

As shown in Figure 4 the wafers are passed under slabs of boron nitride A held on a quartz frame a short distance above the wafers. The slabs should be one inch wider than the wafer diameter to eliminate the edge effects. The atmosphere in the furnace tube should be as static as possible, and is maintained by a slow trickle of nitrogen introduced at one end.

With diffused layers of 50-200Ω/cm-2 variations of $\pm$1-3% are obtained.

Arsenic Doping

Arsenic doping from doped glass deposited at 500°C is achieved using a system similar to the one shown in Figure 1. A gas mixture of arsenic doped tetra ethyl ortho silicate, oxygen and nitrogen is passed through the furnace at 500°C. Glass films of 2000-3000 $\overset{\circ}{A}$ are deposited with a uniformity of $\pm$50$\overset{\circ}{A}$. These films are used as diffusion sources giving doping uniformity of $\pm$5-10% with a thruput of one slice per minute.

The total cost of the system is under $25,000, whereas commercially available units of $50,000 give lower thruput.

Continuous Glass Deposition

The system can also be used for conventional Continuous Glass Deposition for surface protection and multi-layer inter-connections in a similar manner.

Other Uses

For non contaminating furnace processes such as oxidation wafers may be dump transferred from IMS carriers into compatible quartz carriers. These may be placed on the flat quartz boats and

carrier through the furnace. The thruput of the furnace used in this manner is very high, as up to 200 wafers are in the hot zone at any one time and the processing is continuous.

Summary of Specifications

Useful furnace tube length	32 inches
Number of wafers in hot zone	14-two inch wafers
Speed of travel through furnace	0-4-1/2 inch/min.
Temperature of operation	Up to 1150°C
Continuous Operation	
Thruput for 1/2 hr. diffusion time	28-two inch wafers/hr.
Recovery time	Zero
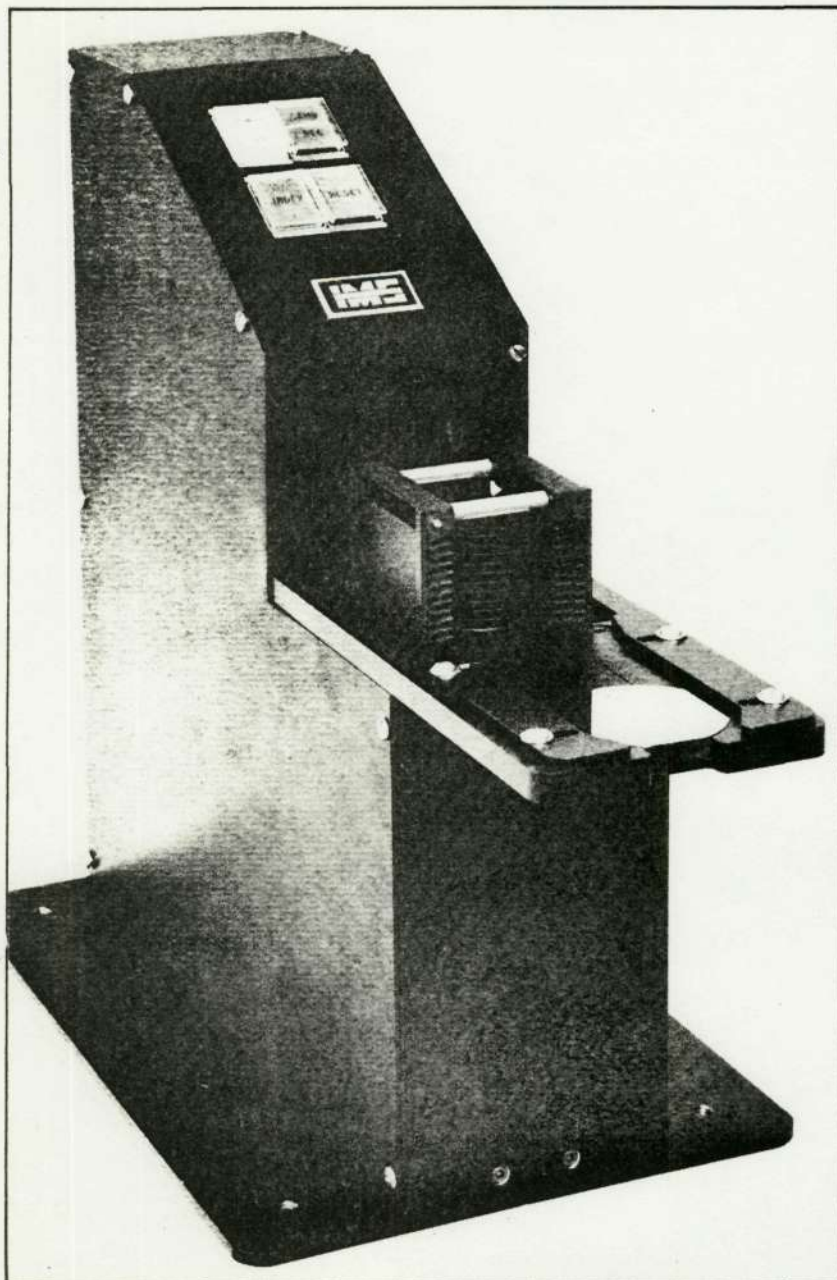
6100 SERIES

The starting point for all Air Bearing operations is the transition from manual transport of wafers to mass handling in carriers. Once loaded, human-to-wafer contact ceases for the remaining transport and processing of whole wafers. An operator selects individual wafers to enter the Loader-Unloader. The Air Bearing carries the wafers into a slot of the carrier which then indexes up to present the next empty slot of the carrier. If the need arises the same machine can be used to unload wafers from their carriers. This, then is the beginning of a proprietary method for handling wafers which allows the mechanization of almost all processes in the wafer fabrication area. Field tests have found the IMS line to offer consistant advantages of increased throughput, lower labor and material cost, increased yields and greatly reduced wafer breakage and damage. Operator speed is a major feature of the 6100 Series setting it apart from current methods. Hand loading operations require from five to ten seconds for each wafer loaded. The 6100 Series allows throughput of one wafer per second.

Carrier loading and/or unloading can be done manually or automatically at the option of the operator. During these operations a sensor is used to ascertain the presence or absence of a wafer, which sends a signal to the indexing platform. In the loading mode, the carrier is advanced one slot at a time until all slots are filled or the operator demands

another carrier. In the unload state the logic ignores all empty slots, scanning until a wafer is presented for unloading. The 6100 Series is adaptable to all phases of wafer fabrication to reduce handling losses.

UTILITIES REQUIRED

ELECTRIC POWER
115 V.A.C. 50/60 Hz
250 W

CLEAN DRY COMPRESSED AIR OR NITROGEN
Min. Pressure 25 PSI
Max. Pressure 100 PSI

DIMENSIONS
Loader/Unloader
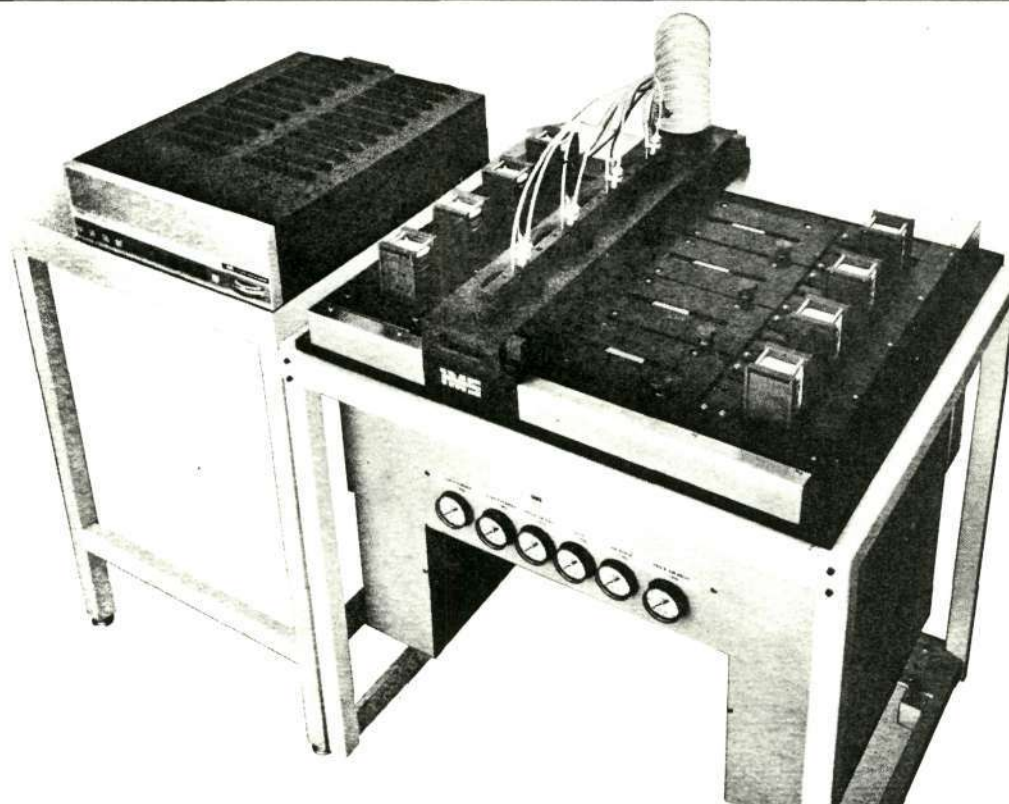Height 14 1/2"
Base Width 8"
Base Length 12"

POWER SUPPLY
Height 8 1/4"
Width 11"
Length 11"

CONNECTING CABLE LENGTH 6'
(Power supply to Loader/Unloader)

IMS

AUTOMATIC PHOTORESIST COATER

6600 SERIES

The 6600 Series of Automatic Photoresist Coaters are designed to accommodate all wafer sizes used throughout the semiconductor industry. Wafers may range in diameter from 0.875 inches to 3.50 inches: All may be of one size or vary according to individual requirements of simultaneous processing. The Linear Air Bearing System without human or other mechanical contact gently unloads wafers from the input carriers, transports them to and from spin chucks, then loads them into output carriers for baking. Operator functions are limited to supplying filled input carriers, removing loaded output carriers and actuating a start button to initiate coating cycles.

The system is completely automatic — an entire coating cycle is controlled by pre-set programs. Cycles are electronically controlled by plug-in cards which control times, acceleration ramps and spin speeds. Process functions may include: Spray wash with a cleaning solvent, spin drying; pre-coating with materials such as silane-xylene, spin drying; coating with photoresist and spin drying. If a wafer is not present in a carrier or on one of the four spindles, the dispense and spin cycles on that row are automatically inhibited without effecting the operation on any of the other tracks.

In use, the system has been found to increase yield as well as cut photoresist costs: Compared to other methods, only 1/4 to 1/3 the amount of photoresist is required. Coating thickness varia-

tions of less than 100A° across the wafer surface are typical. The system measureably prevents damage to photoresist when both sides of the wafer are coated as well as greatly reducing most major causes of wafer damage and breakage. Production rates as high as 1200 wafers per hour can be achieved, depending upon the length of the spin cycle. A typical coating cycle of 20 seconds will yield a throughput of 650 wafers per hour. Operating programs are modular and easily changed.

SPECIFICATIONS

WAFER SIZE
Range .875" to 3.5"

PRODUCTION RATE
Wafers/hr. $= \dfrac{3600}{.25t_{cp} +1.1}$
where t_{cp} = length of spin cycle in sec.

CARRIER CAPACITY
25 wafers

CARRIER TEMPERATURE LIMIT
CTFE 200°C
Anodized aluminum 250°C

SPIN MOTOR SPEED
0 to 10,000 RPM

SPIN MOTOR ACCELERATION
0 to 7,000 RPM continuously variable from 45 ms. to 120 seconds

DISPENSE PUMP VOLUME
Adjustable 0 to 5 cc.

SUPPLY REQUIREMENTS
DRY AIR CONSUMPTION
1.5 C.F.M. STP

VACUUM REQUIREMENTS
15" Hg. for vacuum chuck
5" H_2O for exhaust manifold 200 C.F.M.

DISPENSE PUMP AIR CONSUMPTION
6 cu. in. per pump cycle @ STP

ELECTRICAL
POWER REQUIREMENTS
1 KW peak @ 117 V.A.C. or 230 V.A.C., 50/60 Hz

CONNECTING CABLES
1 - 6 ft., 17 conductor cable for dispense
1 - 6 ft., 37 conductor cable for signals
1 - 6 ft., 26 conductor cable for power distribution
1 - 6 ft., 3 conductor power cable

MECHANICAL
WEIGHT
125 pounds (approx.)

PUMP LIFE
>2 million cycles

IMS

AUTOMATIC DEVELOPER SYSTEM

7400 SERIES
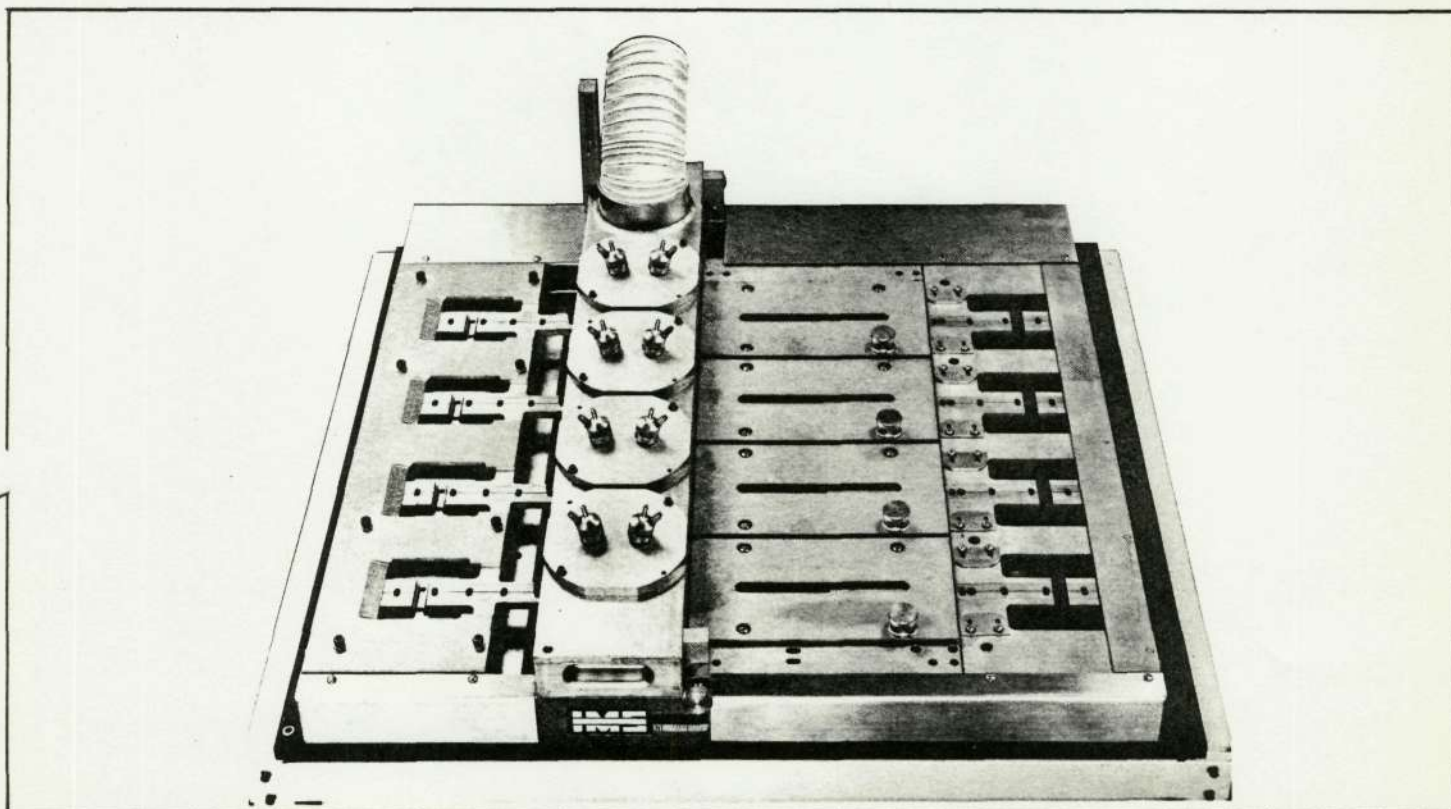
The Industrial Modular System Photoresist Spray Developers have basically the same appearance and configuration as the 6600 Series Coaters. Differing are the exhaust bar containing the spray nozzles, as well as the spray program. From the point of view of the operator, however, the machines are quite similar. Four standard aluminum carriers, containing up to 25 wafers each, are loaded into the input side of the Developer. A start button is pressed and wafers are carried through the spray development cycle four at a time, then reloaded into carriers at the output area.

A typical program for developing a film of KTFR approximately one micron thick: Developer is sprayed for five seconds at 800 RPM; during the next two seconds developer and rinser are sprayed simultaneously, followed by a rinse of five seconds during which the spin speed is accelerated to 4,000 RPM. A five-second spin-dry completes the process for a total of 17 seconds. Using the IMS De-

veloper System with a typical develop cycle, throughput of 650-700 wafers per hour can be expected. In turn, one micron lines with one micron spacing are produced, with edge definition of better than 0.1 micron. Each of the dispense heads mounted over the four spinning chucks has the capability of accommodating three atomizing nozzles for the dispense of developer, fixer and wash. The distance of the atomizing nozzles above the wafer can be varied to obtain optimum developing. The

use of aspirating nozzles replaces the need for pressurized containers and reduces potential safety hazards. Sequential or overlapping atomized sprays can be programmed as desired.

SPECIFICATIONS

WAFER SIZE
Range .875" to 3.5"

PRODUCTION RATE
Wafers/hr. = 3600
$.25t_{cp} + 1.1$
where $t_{cp} = $ length of spin cycle in sec.

CARRIER CAPACITY
25 wafers

CARRIER TEMPERATURE LIMIT
CTFE 200°C
Anodized aluminum 250°C

SPIN MOTOR SPEED
0 to 10,000 RPM

SPIN MOTOR ACCELERATION
0 to 7,000 RPM continuously variable from 45 ms. to 120 seconds

ASPIRATION 10cc/Min.

SUPPLY REQUIREMENTS

DRY AIR CONSUMPTION
1.5 C.F.M. STP

VACUUM REQUIREMENTS
15" Hg. for vacuum chuck
5" H_2O for exhaust manifold 200 C.F.M.

ELECTRICAL

POWER REQUIREMENTS
1 KW peak @ 117 V.A.C. or 230 V.A.C., 50/60 Hz

CONNECTING CABLES
1 - 6 ft., 17 conductor cable for dispense
1 - 6 ft., 37 conductor cable for signals
1 - 6 ft., 26 conductor cable for power distribution
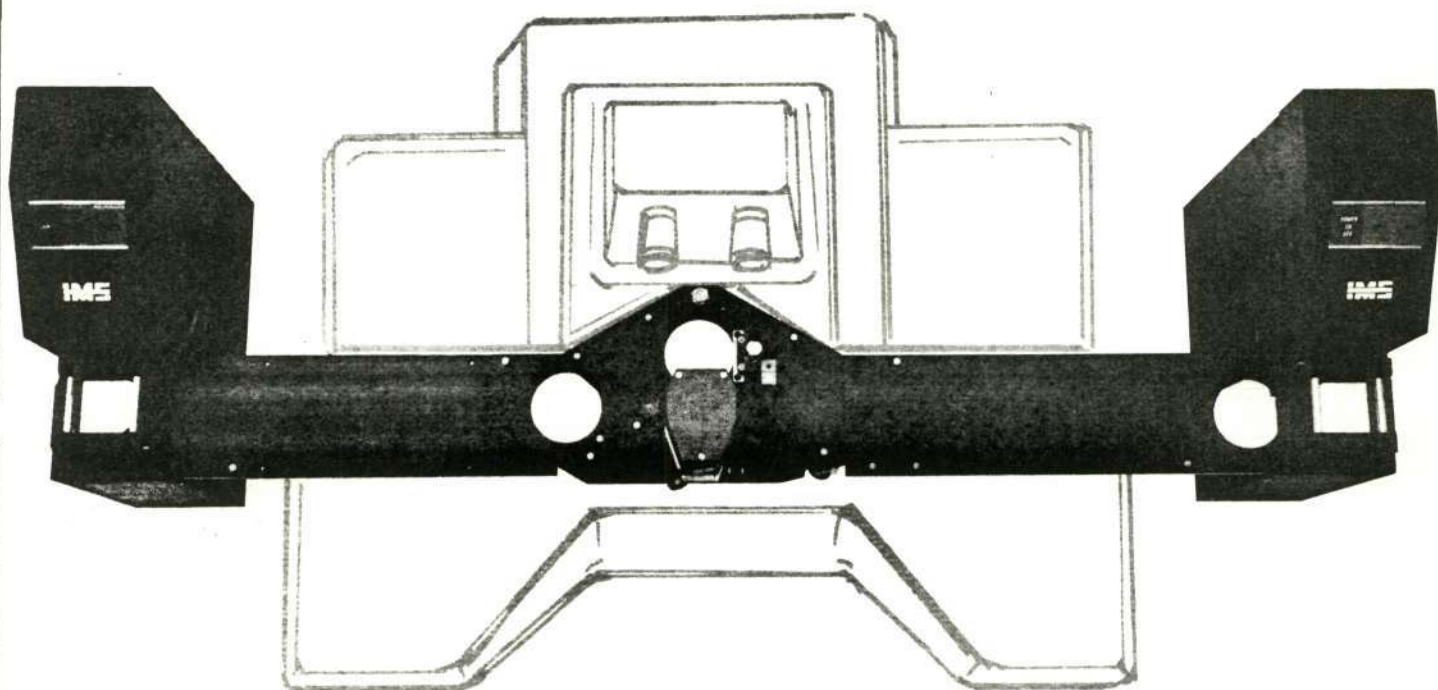1 - 6 ft., 3 conductor power cable

MECHANICAL

WEIGHT
125 pounds (approx.)

8200 SERIES

The IMS 8200 Series Wafer Feed Systems are designed to automatically unload wafers from a standard IMS carrier, orient them using the wafer flat as a reference, carry them into a Mask Aligner for fine alignment and exposure and then transfer them into another carrier. Proprietary Air Bearings are used both for the linear transportation of the wafers and for their angular orientation prior to fine alignment. These provide extremely gentle handling of the wafers while reducing both wafer breakage and scratching to a significant degree.

During normal operation, the sequence of the machine is automatic and each step is initiated by the corresponding action on the aligner. This means that the operator can use the Mask Aligner in the normal manner and the 8200 Feed System will load and unload the wafers without any direct command from the operator.
In a complete alignment sequence each wafer goes through four steps:

A. The wafer is removed from its input carrier and transported on an Air Bearing to a buffer position where it waits until the pre-alignment chuck is clear.

B. The wafer is transferred to the pre-alignment fixture where it is rotated on air jets until the flat or notch is centered on an optical sensor. This position is maintained by vacuum.

C. The wafer is carried into the Mask Aligner for fine alignment and exposure.

D. The wafer is taken out of the aligner and again carried on an Air Bearing into the output carrier.

INDUSTRIAL MODULAR SYSTEMS CORPORATION
3570 RYDER STREET SANTA CLARA, CA 95050 (408) 732-5330 TWX (910) 339-9211

FACILITIES REQUIRED

(In addition to Mask Aligner needs)

ELECTRIC POWER
115 V.A.C. 50/60 Hz

COMPRESSED NITROGEN OR VERY CLEAN AIR
Min. Pressure 30 PSI
Max. Pressure 100 PSI
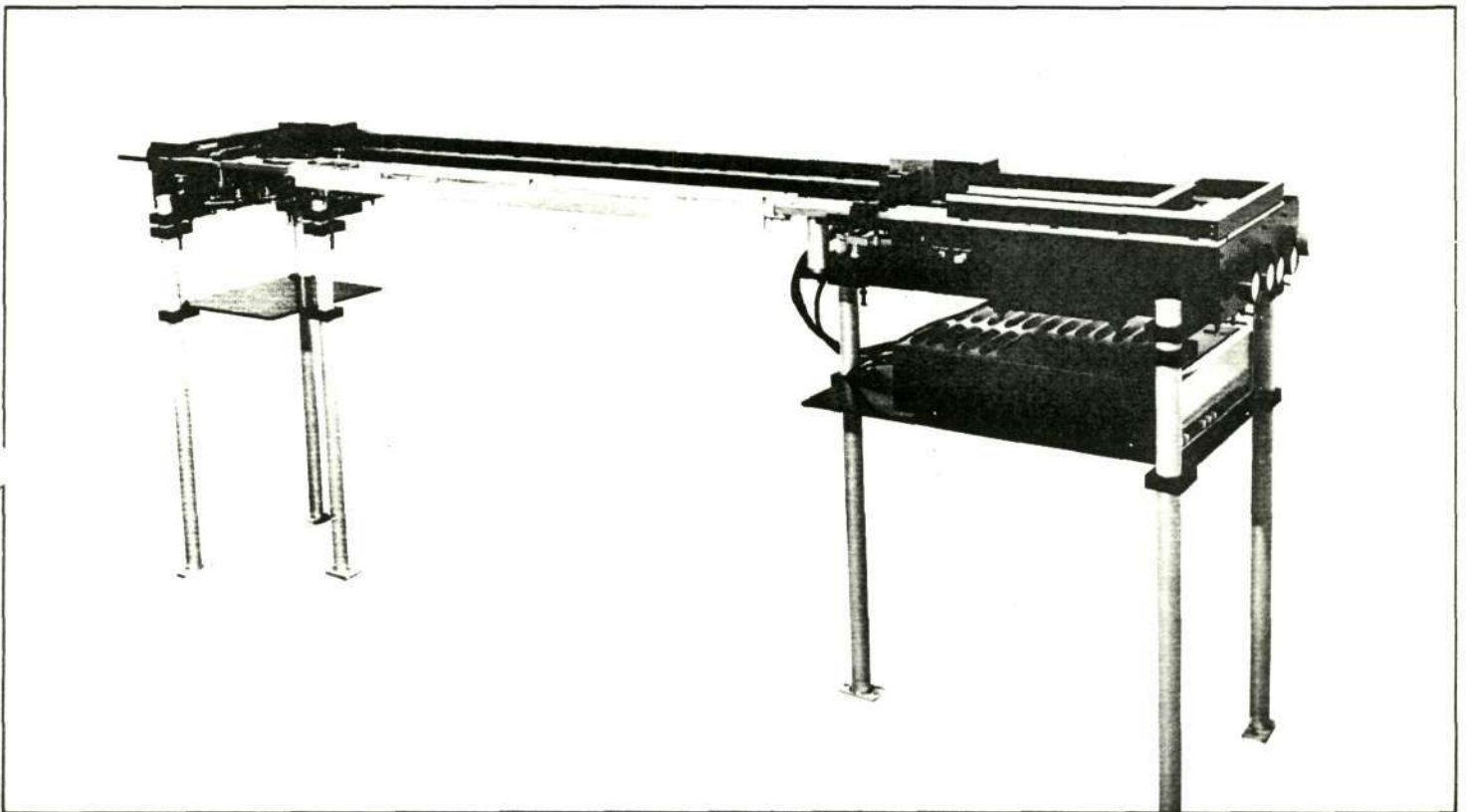
MAX. FLOWS
1 C.F.M. at 30 PSI

VACUUM
Min. Pressure 15" Hg.

IMS

**DIFFUSION PUSHER
TRANSPORT
SYSTEM**

9100 SERIES

Mechanization of the diffusion process has been achieved by making it a continuous rather than a batch process, and by passing the wafers completely through the furnace tube. The system is a closed track which passes boats through a furnace and recirculates them around the outside. Wafers are transferred from carriers to flat quartz boats, passed in a continuous line through the furnace tube and reloaded into exit carriers. The boats are then returned to the front of the furnace for recycling. While the quartz boats are carried by Air Bearings outside the furnace, they slide along guide rails inside the furnace. A mechanical pusher moves the boats through the furnace with a controlled variable speed from zero to 4.5 inches per minute.

This furnace transport system can be used in conjunction with many doping methods. Where doped gas is used, the furnace tube has bulkheads at either end through which the boats pass. These bulkheads serve to isolate the doped gas in the center of the furnace and to provide a curtain of gas at either end to prevent escape of the doped gas from the furnace hot zone. This precaution is unnecessary where dopant is spun onto the wafer surface prior to entering the furnace. The system may also be used for diffusion using vertical wafers together with boron nitride wafers stacked in a boat. In this case, quartz boats, compatible with the IMS carrier system can be used and loaded directly into the front end of the

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furnace. Alternatively, boron inside slabs may be supported permanently inside the furnace tube on a quartz frame. In this configuration the wafers lie flat and pass about a quarter of an inch below the stationary boron inside slabs. The advantages of this system are considerable. Since the wafers pass down the length of the furnace tube, every wafer experiences the identical integrated thermal and gas environment, making unimportant any fluctuations in temperature and gas composition along the furnace length. This gives diffusion profiles far greater uniformity than can be obtained by conventional batch processes. Also, since the process is continuous, there is no recovery time between runs, resulting in improved throughput. Even higher throughput can be achieved by raising the temperature of the end zones. This, in turn permits the use of an added ten inches of furnace length.

FACILITIES REQUIRED

ELECTRICAL
2 KW peak @ 117 V.A.C. or 230 V.A.C., 50/60 Hz

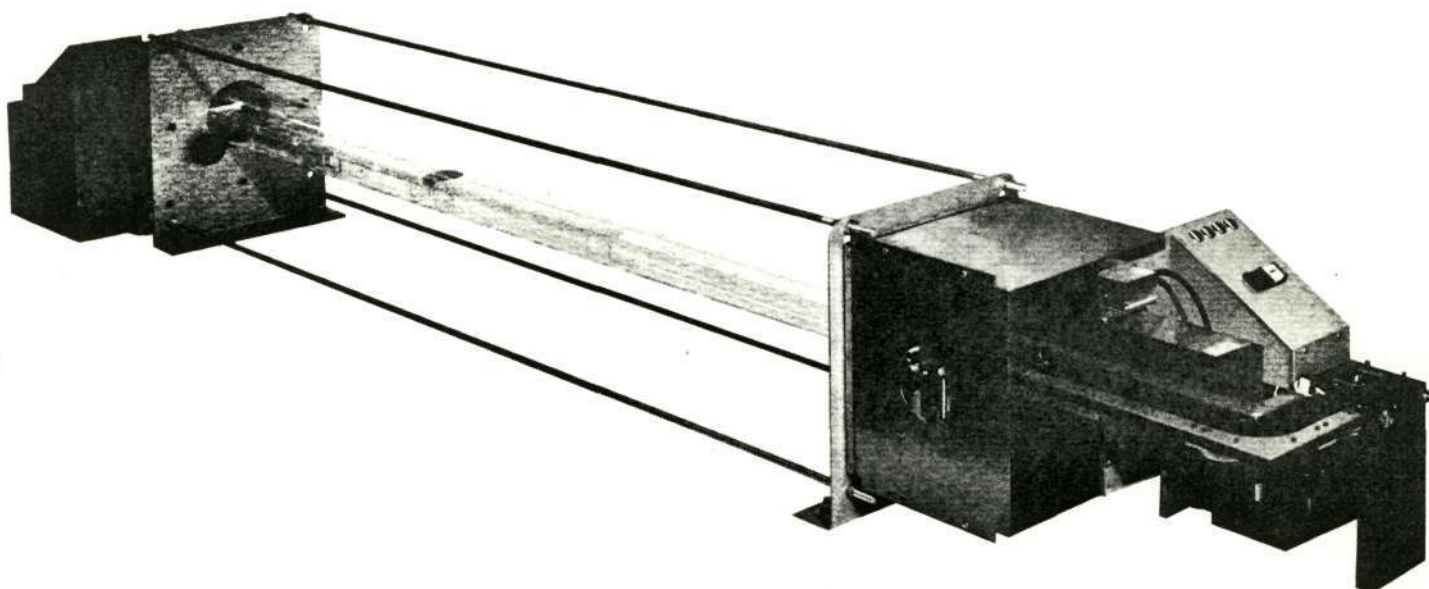DRY AIR OR NITROGEN
8 C.F.M. @ 65 P.S.I.G.

VACUUM
15" Hg

9200 SERIES

The 9200 Series is a furnace transport system designed to rapidly quench semiconductor wafers from high temperatures. Cooling from temperatures up to 1150°C to room temperature can be accomplished both safely and reproducibly. This is most useful for minority carrier lifetime control after gold diffusion, and for spike alloying. Wafers are automatically removed from the carrier and transferred individually in the quartz gas bearing track into the furnace to the soak position. The wafer is allowed to come to temperature and soak for a predetermined time.

After the soak time, the track is pulsed with high velocity gas which couples to the wafer and accelerates it from the furnace tube in 0.2 seconds to a water cooled vacuum plate. The wafer is cooled to near room temperature while the next wafer to be processed is carried into the tube. The "quenched" wafer is transported from the chill plate to a waiting carrier which acts as buffer storage. This sequence repeats itself automatically until all wafers have been cycled, when the unload and load carriers are removed and replaced by a fresh run.

When used for minority carrier lifetime control, gold diffusion takes place prior to processing through the Rapid Quench Furnace; for example, during emitter diffusion. The Rapid Quench Furnace handles one wafer at a time which would make the throughput low if the diffusion time were added to the soak cycle. Since

there is almost no thermal load on the furnace, the heat-up time for the wafers is very rapid. This, together with the rapid quench and precise soak time, makes the furnace very suitable for aluminum and gold spike alloying.

SPECIFICATIONS

ELECTRICAL
250 Watts peak @ 117 V.A.C. or 230 V.A.C., 50/60 Hz
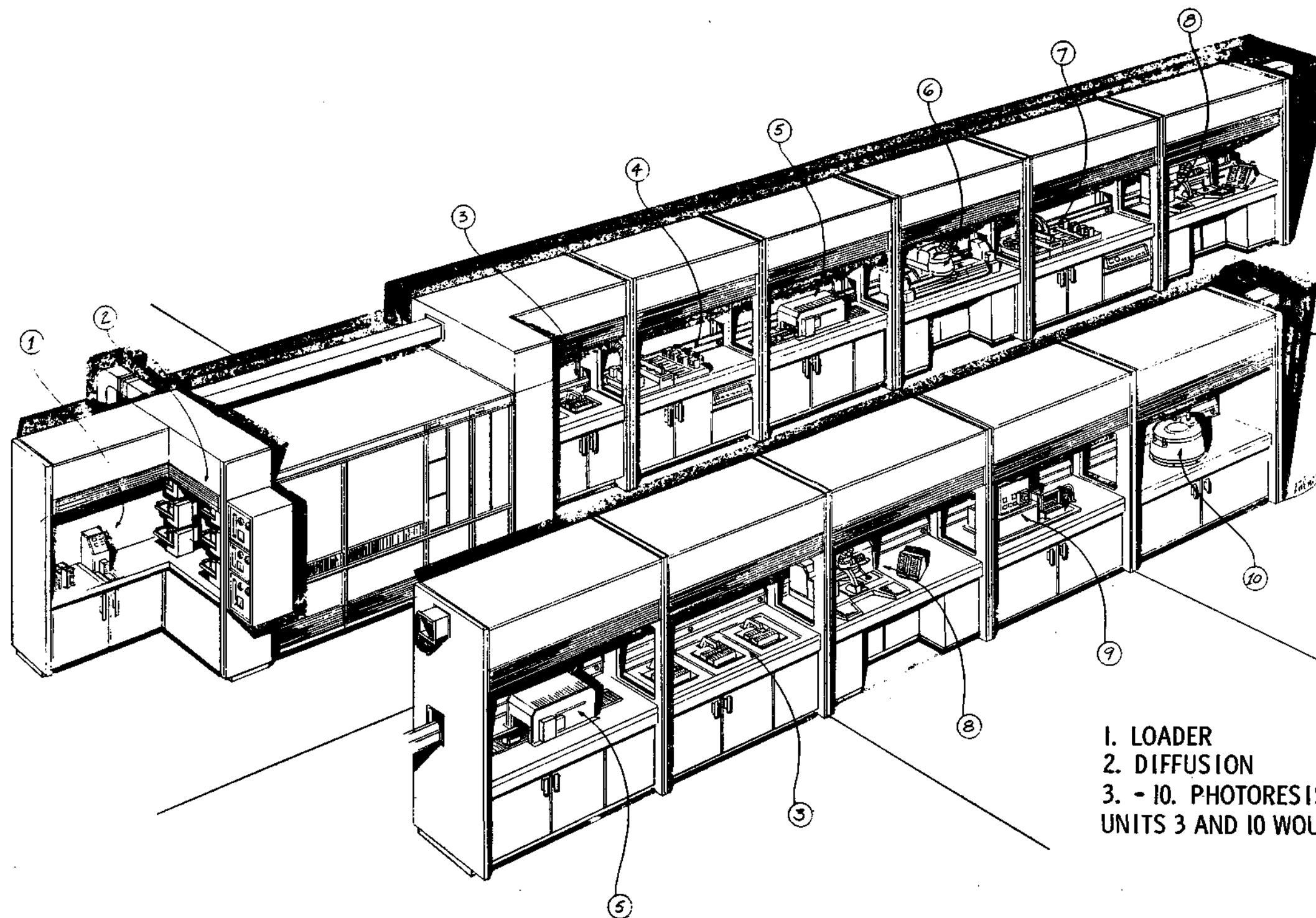
DRY AIR OR NITROGEN
2 C.F.M. @ 40 P.S.I.G.

VACUUM
20" Hg

WATER
0.5 G.P.M. @ 60 P.S.I.G.

1. LOADER
2. DIFFUSION
3. - 10. PHOTORESIST AND ETCHING
UNITS 3 AND 10 WOULD ALSO SUFFICE FOR CLEANING.

AUTOMATED EQUIPMENT IN LAMINAR FLOW BENCHES (BY I.M.S.)

APPENDIX D

AUTOMATED DIFFUSION

(Supervisory Mode)

AN AUTOMATIC DIFFUSION PROCESS FACILITY

BRUCE Industrial Controls, Inc.

An Automatic Diffusion Process Facility

J. S. ANDERSON
Bruce Industrial Controls

ABSTRACT

The production of semiconductor devices for an increasingly competitive market has resulted in the demand for a new generation of sophisticated production equipment. Improved yields and reduced operating costs were the goals sought when the project of automating the diffusion process was undertaken.

Lower operating costs are realizable by repackaging the furnaces - reducing the floor space requirements, while simultaneously reducing air conditioning loads and power requirements.

Improved, more consistent yields are attainable by properly defining the critical process parameters, and applying precision controls to these variables.

"Witch-craft" and "artistry" have been eliminated from the process. Precision control of the time, temperaturea and gas composition variables, as well as the ability to continuously examine data on all second order and peripheral variables - for either immediate corrective action, or subsequent analysis - has provided the engineer with a tool with which to transform the "art" to a science.

The justification for automating any process lies in the ability to reduce the cost of producing a saleable product. Cost reductions assume several forms when applied to the diffusion process:

1. Reduced power and utility costs/unit product (improved efficiency)

2. Increased saleable product/batch processed (increased yield)

3. Decreased human intervention/unit product

In the automatic system described herein, all of these savings are realizable; with yet the additional benefits to the user of having continuous information flow on all of the process variables, presented in such a manner as to allow instant intervention, or storage for future analysis.

Re-Packaging for improved efficiency

In the past decade, one of the most significant improvements made to diffusion furnaces was the substitution of loss mass, ceramic fiber insulation materials for the previously used fire brick insulations. This substitution allowed the furnace to become much more controllable and responsive to minor changes in controller demands. Un-

fortunately, the thermal losses of the furnace simultaneously increased, and it became necessary to remove excess heat from the immediate area of the furnace by forced convection.

In normal operation, a diffusion furnace draws approximately 3.5 KW when controlling at the operating temperature. Of this input, approximately 30% is lost to the diffusion room, in the form of losses from the ends of the tube, radiation from the process tube, heat carried away in the effluent gas, etc. The remaining 70% is lost in forced convection, being that heat that is transmitted through the insulation and conveyed to the cooling air. This air is usually drawn through a heat exchanger which can be expected to remove 60 to 70% of the heat it contains and then redistributed to the room. With furnaces operating in this fashion, a diffusion room will generally be designed by the rule-of-thumb that each diffusion furnace tube demands one ton of air-conditioning in order to maintain the room at a reasonable comfort level.

It is possible to redesign the packaging of the furnaces, however, so that cool air is brought in from outside the building, passed over the furnaces to remove waste heat and then exhausted to the outside, eliminating recycling it into the room and thereby raising the room's tempera-
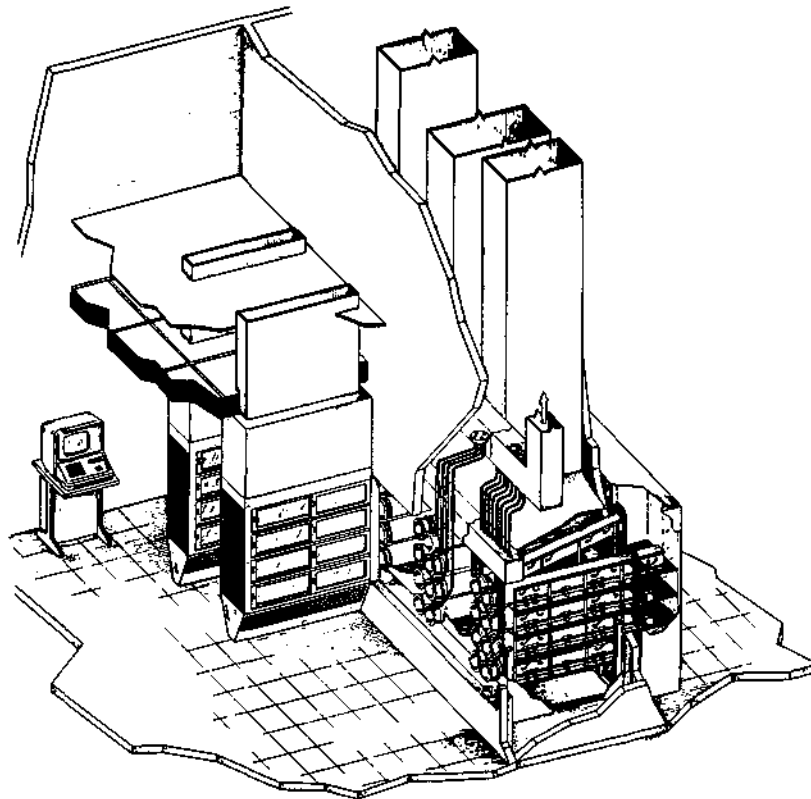

FIGURE 1: Artist's concept of multi-tube installation. Air flow pattern, exhaust gas scavengers, loading stations & remote Operator's console are shown.

ture. This technique of enclosing the furnaces within insulated walls and utilizing outside air in the manner described, as well as providing radiation shields to reflect the heat normally lost from the ends of the furnaces, allows for reducing the necessary air-conditioning by approximately 75%, representing an estimated initial savings of $750.00 per tube.
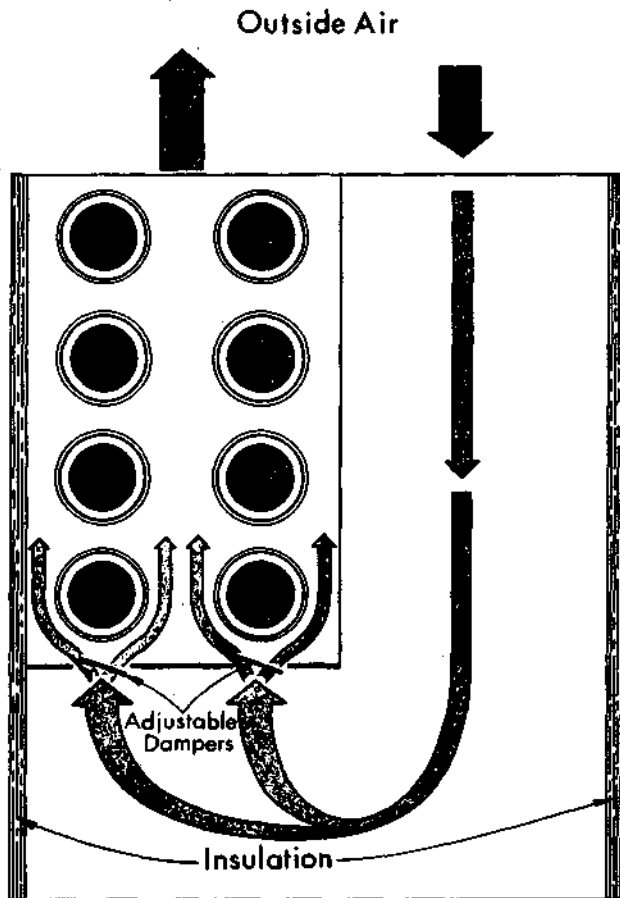
Outside Air

FIGURE 2: This drawing illustrates how outside air is utilized to cool the furnace tubes, then exhausted to outside.

The use of radiation shields, employed at both ends of the furnaces, not only reduces the heat transmitted to the room but also reduces the steady state power requirements of the furnaces by 10 to 15%. This same repackaging of the furnaces into octal clusters, two tubes wide and four tubes high, wherein the top tube centerline is approximately 63" above the floor level and the bottom tube is 29" above floor level - both heights readily within the comfortable working range of a female operator - allows for a reduction in floor space to approximately 60% of that originally planned upon. Water requirements are reduced to 1/12th of what a conventional furnace would require, and the water serves only to cool the SCRs, in lieu of cooling the air. The water cooled SCR packages assist in overall space reduction, each package being approximately 1/6th the size of a conventional, convection cooled package.

Increased Yields

The diffusion process is a batch process wherein a quantity of work is placed in a diffusion furnace, subjected to specific environmental conditions for a specific time and then withdrawn from the furnace. In order to achieve a continuous flow of product each furnace tube is generally designated to perform a specific operation, and this particular furnace is loaded with batch after batch of product upon which this operation is to be performed. In order to achieve uniform results from load to load, it is absolutely necessary that each batch of work experience precisely the same environmental conditions for the same length of time that every other batch experiences. Therefore, it follows that the environment (temperature and gas composition) must be always the same, and that the time during which the work is exposed to this environment must not vary, load to load.

When the parameters that comprise the environment and the time parameter are precisely controlled, significant improvements in yield, in the form of predictable product quality from load to load can be realized. Analysis of the performance of the diffusion process showed that of the three critical process parameters (i.e., temperature, gas composition and time), only two were under any degree of control in most instances. By far, the greatest attention has historically been devoted to the control of furnace temperatures. Control of the process gas flows has been subjected to a considerably lower degree of scrutiny, and the time parameter, in a great majority of present day diffusion operations is very poorly regulated.

The control of the time parameter, which includes not only the time that the work is at rest in the hot zone, but also the length of time involved in transferring the work into and out of this hot zone, has generally been operator dependent. It should be readily apparent that even the most skillful operator could not be expected to:

1. manually push the work into the furnace at precisely the same rate, day after day after day.

2. ascertain that the work came to rest in precisely the same position in the furnace chamber, day after day after day.

3. manually withdraw the work from the furnace at precisely the same rate, day after day after day.

It was further noted that quite often an audible timer was employed to signal the end of a process run, alerting the operator to return and begin the withdrawal of the work from the furnace tube. For any number of easily rationalizable reasons the operator quite frequently failed to begin the withdrawal procedure at the precisely appointed time, and as a result, no single load could be expected to experience exactly the same processing as any other.
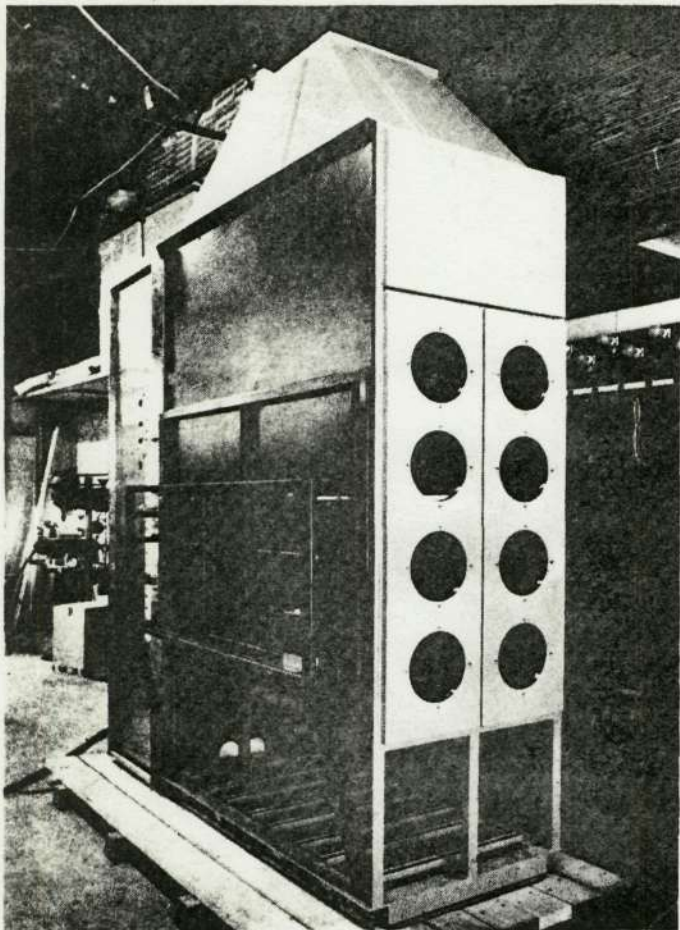
FIGURE 3: Eight tube module during initial construction, showing modular design.
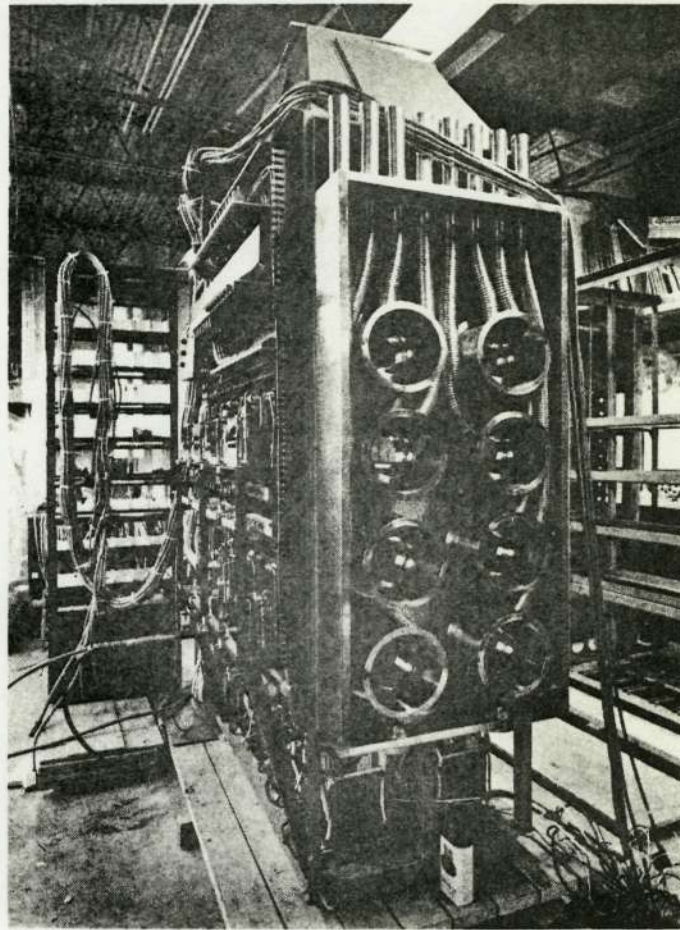

FIGURE 4: Same module during final construction stages, showing exhaust gas scavenger system installed.
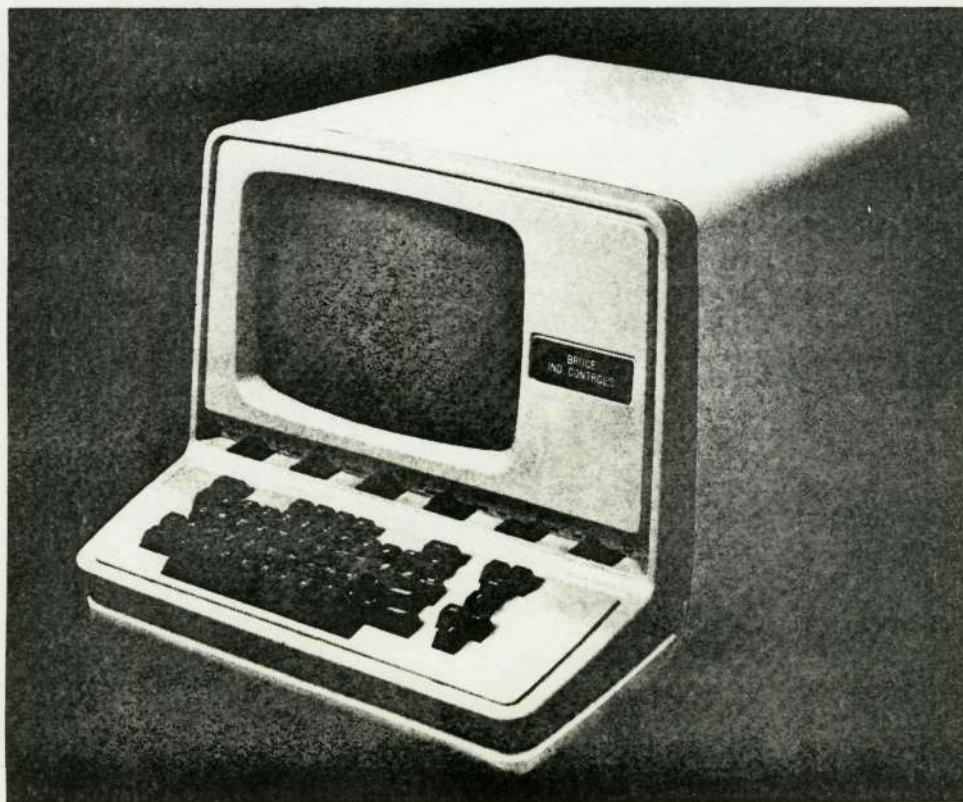

FIGURE 5: Remote Operator's console.

A significant improvement in process repeatability was achieved by automating the time parameter. This automation dealt with the adaptation of an existing, reversible, linear drive mechanism to transport the work into the furnace, hold it in position for a predetermined length of time and then withdraw the work from the furnace. Operator intervention is minimized, to the extent that it is only necessary for the operator to bring the work to the waiting loader and depress a push button. The cycle is automatic from that instant, to the extent that the work is transported into the furnace at a specific, predetermined rate - held at a specific point within the furnace flat zone for some specific period of time and then withdrawn from the furnace back to the load position at some specific, predetermined rate (which rate is set independently from the insertion rate).

The second area wherein significant improvements have been made, leading towards total process repeatability, lies in the control of gas flows. At the present time it is almost universal practice to employ volumetric type flow meters, which function by virtue of a fixed orifice in the path of a gas stream. The volume of gas, however, which passes through the fixed orifice and into the process tube is dependent upon the pressure and temperature of the gas, and leaves no record as it does so. Indeed, anyone who has tried to set up a flow will admit that he has had to "follow the bouncing ball", mentally judge the average ball location and assume that he was "close enough". He may have indeed been "close enough" at that instant, but at various times during the day when the gas pressures vary due to increased or decreased usage, that flow will change - and worse, there is no way to tie variations in yield or device parameters to a changed gas flow, because there is no record of the flow excursions.

Several manufacturers now offer Mass Flow Controllers, designed to sense the actual amount of gas flowing past a transducer; to regulate the opening of a valve in the gas stream as a function of the transducer signal; and, to precisely control the mass of gas per unit time which enters the diffusion process tube.

Further, these devices are designed to provide an output signal proportional to the amount of gas flowing through them, which signal can be recorded and compared against product performance. Utilization of these Mass Flow Controllers allows for precision control of gas compositions.

The timing devices which regulate the sequencing of work transfer events are tied into the gas sequencing devices so that changes in flows or composition of the gas in the process tube are initiated at precisely the same instant, run after run. The precision control of gas flows, as well as the precision control of load, unload and soak times,

coupled with the precise control of temperature, create the proper environment for the achievement of reproducible product, hence improved, predictable yields.

Decreased Human Intervention

In an automated system, the only requirement for operator attention is prior to and subsequent to the actual processing of the devices. The individual wafers are manually aligned on a quartz boat at some other location, and then this boat is positioned on the automatic loading device by the operator, who then depresses a push-button to start the loader.

In addition to having relieved the operator from the responsibility of loading and unloading the furnace, the system is designed to allow her to be free for other duties, completely ignoring the furnace until informed that the work is finished and ready for the next station. The system accomplishes this by virtue of the built in, self policing characteristics which are designed to sound an alarm if any of the controlled or monitored functions fail, or go out of pre-set limits.

Because the automatic system generally encompasses a number of furnace tubes it has been found expedient to provide a central annunciator, from which information concerning either an individual furnace, or the system as a whole, can be instantly presented to the operator. This annunciator has taken the form of a Cathode Ray Tube which is coupled with an alpha-numeric keyboard. The function of the CRT is to point out instantly where a problem exists, and to pin-point exactly what the problem is. In order to accomplish this, the system has been set up so that by the simple manipulation of the proper keys on the CRT console, a complete page of information pertinent to the desired furnace tube is displayed.

C.R.T. DISPLAY FORMAT

			ACTUAL	MEMORY
C7 BORON DRIVE-IN	09:25:36			
CONSULT ENG DEPT BEFORE LOADING		– –01 LOAD	12.313	12.310
VAR 05 RANGE 15.000 LIMIT 00/.050MV		– –02 MNTR	12.315	12.314
SELECT VAR ( ) 01-19, E1-E8, A1-A8, N, M		– –03 CNTR	12.317	12.318
		– –04 MNTR	12.316	12.316
E T EVENT	OCCURS MEMORY	– –05 SRCE	12.314	12.315
– –1 – BOAT RACE	00:01:30 00:01:30	– –06		
– –2 1 N2 BUB ON	00:05:10 00:05:10	–*–07 FLSK	6.306	10.005
– –3 2 NH3 ON	00:05:30 00:05:30	– –08 SFUR	5.007	5.012
– –4 – STABILIZE	00:16:00 00:16:00	– –09 PHTR	7.913	7.913
– –5 3 BU&NH3 OFF	06:30:00 06:30:00	– –10		
– –6 4 BOAT OUT	06:45:30 06:45:30	– –11		
– –7 – BOAT RACE	06:45:56 06:45:56	– –12 N2FL	3.373	3.375
– –8		– –13 O2FL	5.882	5.880
		– –14 N2BU	0.007	4.713
		– –15		
– –A1 THERMOCOMP	– –A5 FLASK LEVEL	– –16		
– –A2 SCR TEMP	– –A6 VEST HTR COLD	– –17		
– –A3 DOOR OPEN	– –A7 HTR TAPE COLD	– –18 %O2	3.727	3.725
– –A4	– –A8	– –19 %H2O	9.315	9.316

LEGEND:

01	LOAD	Load End Control T.C.	09	PHTR	Gas Preheater Temperature
02	MNTR	Load End Excess Temp. T.C.	12	N2FL	Nitrogen Flow
03	CNTR	Center Control T.C.	13	O2FL	Oxygen Flow
04	MNTR	Source End Excess Temp. T.C.	14	N2BU	Nitrogen Bubbler Flow
05	SRCE	Source End Control T.C.	18	%O2	Percent Oxygen Content
07	FLSK	Source Flask Temperature	19	%H2O	Parts Per Million Water Vapor
08	SFUR	Source Furnace Temperature			

FIGURE 6: Typical information presentation for individual furnace tube.

A title block presents information identifying the tube number and the process which is being run, and space has been allocated for the temporary insertion of information such as specific instructions regarding the work in that tube. All of the controlled parameters (i.e., temperatures, gas flows) are identified and their values are presented in two columns. One of the columns, entitled "Actual" presents the immediate value of that parameter, as sensed by the control transducer, while the second column, entitled "Memory", presents the value that the transducer should be displaying. This "Memory" value is the value for that parameter which will result in ideal product, and is the value that was inserted into core memory when the process was set up.

Associated with each of the "Memory" values is a set of symmetrical, key-board set limits, which determine how far the "Actual" value can wander away from the desired operating value before an alarm is activated. Other variables, not directly controllable (e.g., PPM H_2O, etc.) but which have an influence on the quality of the work being processed are also monitored, presented on the CRT for analysis and bounded with limits so that an alarm will notify the operator if they vary beyond these limits. During normal operation the CRT would be set to display the "System Page", upon which page such information as air duct temperatures, selected gas pressures and general information, applicable to the entire complex is presented.

One of the interesting displays on this page is the calibration display which is used to alarm on the wandering or failure of the digital voltmeter which establishes the "Actual" values of all of the measured variables. The DVM operates on two ranges; the low range (0-15.000 millivolts) is used for the collection of thermocouple information. The high range is 0 to 15.000 volts, is readable to the nearest millivolt and is used to collect data on all of the rest of the monitored variables in the system.

At the prescribed point in every scan cycle, the DVM is checked on both high and low range for "zero" and "span" accuracy against narrowly set limits, and an alarm is activated in the event that the DVM is in error.

Note that each of the individual process tubes is represented by a "0" on the system page. If an alarm condition occurs in one of the tubes, its "0" flashes and an audible alarm sounds. The operator, attracted to the CRT by the audible alarm, observes the flashing "0" and by depressing the proper keys, calls up the page of information pertinent to that particular tube. When this is done, the audible alarm ceases to operate. On the page of information displayed on the tube, however, the variable which has actuated the alarm is immediately identified by a flashing asterisk which appears beside it. Thus, within seconds, the operator has been able to distinguish between several hundred possibilities, to determine which parameter is out of limits, have information presented as to what exactly is the magnitude of the problem and begin corrective action.

Corrective action can involve aborting the cycle, or making compensatory changes to either the erroneous parameter or interacting parameters, directly from the key-board. The setpoints for all of the furnace temperatures and the gas flows are motorized, and driveable from the keyboard. The system has been programmed so that any problems which occur during the course of a cycle will not interfere with the completion of the cycle, but will only notify the operator of their existence. Abortion of a cycle is accomplished only by the operator's depression of a manual withdrawal pushbutton on the loading device.

If, for some reason, it becomes desirable to run a somewhat different process in a particular furnace tube, or to repair some portion of a tube's equipment, that tube can be switched to "Local" control, wherein it is completely removed from system scanning and no alarms will be actuated when its setpoints are changed. There are, however, certain analogue alarms on all of the tubes, which operate independently of the various digital alarms, and which serve to prevent catastrophic failure of the various components. Such alarms are:

Two zones of over temperature control on each of the tubes, which trip the circuit breaker for that tube when they sense an extreme temperature condition.

Temperature sensors on the water cooled SCR heat sink plates, which shut the furnace down when the heat sink temperature becomes abnormally high.

Deviation alarms, operating on each of the three zones of temperature control will illuminate a "Do Not Load" light at the loading station, in the event that any of the control zones is not at proper temperature.

FIGURE 7: Typical "System Page" presentation.

As can be seen from the preceding discussion, the only parameter which is under actual computer control is time. Temperature and gas flow are monitored only, and in the event of computer failure, they will remain exactly as set previously, under analogue control. To completely preclude the possibility of total system shutdown, in the event of computer failure, each of the tubes is equipped with its own back-up clock. This clock consists of a hard wired, printed circuit board which contains all of the process sequencing information for a specific process. During normal, automatic operation, when the computer is in command, the computer is programmed to send out signals to this board on regular intervals to inform the local control network that "Computer has not failed". If this signal does not appear the local board automatically takes over control of the process. This board's clock networks are in forced synchronization with the computer's clock, because at the completion of each step in a process, the computer sends a signal to the local board, updating its clock. Therefore, if the local board does not receive its "Computer has not failed" signal, it takes over the process from almost exactly the specific instant at which the computer lost it, and takes the cycle to completion.

The system thus far described:

Provides for precision control of time, temperature and gas flows.

Alarms when any of these or other monitored variables is out of limits.

Points immediately to where a problem exists.

Is operable under full automatic or local control.

Provides improved yields while allowing reduced operating expenses.

The automated system is a tool, which placed in the hands of an engineer allows him to perform the work previously expected of him in an orderly and precise manner. This same tool can broaden the capabilities of his department by placing at his disposal a wealth of information which can be selectively printed out in hard copy and used at a later date as the basis for determining the effect of other variables on product quality. Or, in the case of manufacture of high reliability components, this information can be used in determining product history and assist in failure analysis.

All of the necessary hardware has been incorporated in this sytem to allow full closed loop, computer supervised control, wherein times, temperatures and gas flows could be continuously adjusted, according to a detailed formula (or even the output of a test machine) to compensate for uncontrollable variables, such as room humidity, etc. Clos-

ing the loop in this fashion would result in still higher percentage yields, but is unfeasible at this time because insufficient data is available on the inter-relationship of supposedly second and third order effect variables. When this data becomes available, it will have been acquired in systems not unlike the one described.
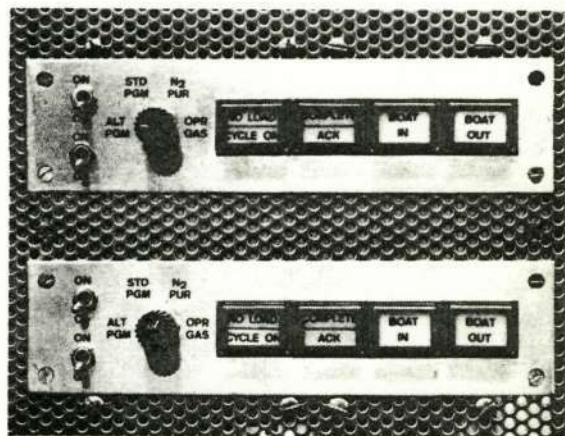

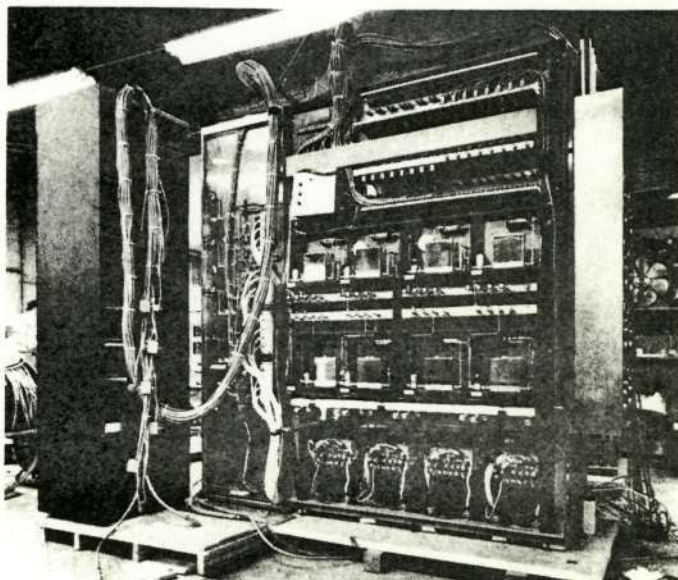FIGURE 8: Operator's controls at loading station.

FIGURE 9: Completed eight tube module prior to shipment, showing gas control systems for all eight tubes, and transformer/SCR packages for four tubes. Cabinet at left houses controls.

APPENDIX E

CLEANING EQUIPMENT

Contamination can seriously alter the performance of semiconductor devices and thus significantly lower manufacturing yields.[1,2] A tiny particle, for instance, can cause a defect in one element of a silicon integrated circuit, which usually renders the entire circuit useless. The advent of MOS technology makes the problem even more serious since this type of transistor is far more sensitive to traces of contamination than the bipolar type.

A major source of contamination is the "high-purity" water supplied by a central deionizing system and piped (sometimes over very long distances) to rinse stations at key manufacturing stages. While this water may approach required purity as it leaves the central system, by the time it arrives at the rinse stations, it is frequently degraded to the point where dissolved and suspended materials can adversely affect device performance.

A related problem is the growing shortage of water. Fluctuations in water supplies and pressures at peak periods are already occurring in some industrial areas of the world. Unfortunately, because high purity water is a powerful solvent, it cannot be stored and must be processed on demand. It is also unfortunate that in conventional rinse systems, more than 80% of the high purity water produced by a central system is discarded to drain virtually uncontaminated.

Millipore Hydronomics solves both of these problems:

1. by processing central system water at the point of use, a concept well documented.[3] *This point-of-use polishing is the only way to insure consistently high-quality rinse water and to avoid variable yields due to sporadic contamination.*

2. by recirculating and repurifying 80% of the rinse water that is usually wasted. *A Millipore Hydronomic System offers significant savings and can pay for itself in less than twelve months in a conventional manufacturing area.*

The Millipore Hydronomics Concept

Water from a central deionizing system is pumped through a Millipore Super-Q System (described on page 4) which consistently produces water of 18 megohm-cm resistivity and removes all particles and microorganisms larger than filter pore size (typically 0.45 or 0.22 micrometer) by means of a Millipore absolute membrane filter. This high purity water flows directly into a rinse tank so that there is no degradation and no chance of variable yields due to sporadic contamination.

Effluent water from the rinse tank is sent to a resistivity control module which can direct it back to the Super-Q System for reprocessing if the quality is greater than some preset level such as 1 megohm-cm; or alternatively, dump the water to drain should the quality be lower than can be economically reprocessed. It is a fact that a large fraction of the water used in conventional rinsing cycles is discarded while at a quality better than 1 megohm-cm; and when a rinse station is not being used, all the high purity water is normally discarded without ever being degraded by device contaminants.

The Economics of Hydronomics

1. In a conventional plant using 60,000 gallons of water per day (100 gpm), it would ordinarily be possible to reduce the volume of raw water processed to 12,000 gallons per day by employing Hydronomic systems.

2. Considering all costs in the production of high purity water (plant depreciation, labor, raw water costs, chemicals, maintenance, etc.), an industrial average cost is accepted as being on the order of 1 cent* per gallon. For a plant capacity of 60,000 gallons per day, the daily cost would be $600.

3. Hydronomic systems can reprocess effluent water of 1 megohm-cm or better at 10% of the cost of processing raw water.

4. Daily water processing costs can then be reduced from $600 to $200 — a daily saving of $400 and a yearly saving of $100,000 (about £40,000).

5. The capital cost of installing Hydronomic systems in such a manufacturing area would be less than $100,000. The pay-back time would be less than 12 months.

Hydronomic systems are modular and they can be added on a where-needed or as-needed basis. Increased water demands of 10 to 20% capacity can be met as they occur without the need of a large capital investment in a new centralized water processing system. The cost of a Hydronomic System is about one-half the cost of central system capacity to meet the same volume requirements.[4]

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* 2.4 cents (U.S.) = 1 new penny (sterling)

Hydronomic System Modules

SUPER-Q SYSTEM

The Super-Q System produces water of 18 megohm-cm resistivity and removes all particles and microorganisms larger than filter pore size (typically 0.45 or 0.22 micrometer) by means of a Millipore absolute membrane filter.

It is a compact system so that it fits easily at the point where high purity water is required and it is modular so that elements can be combined in any desired configuration. The Super-Q System consists basically of the disposable cartridges described below.
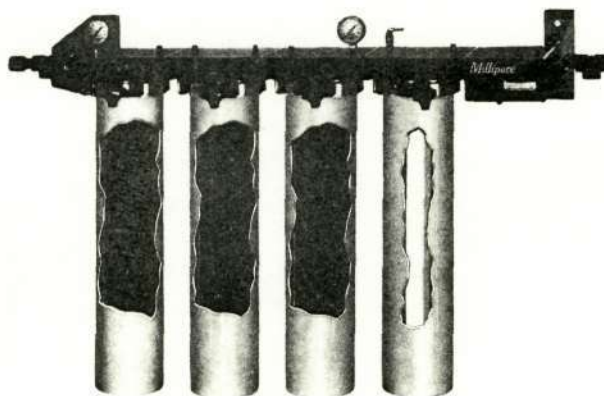
This Super-Q System includes, from left to right, a Super-C Cartridge, two Ion-Ex Cartridges and a Millitube-MF Cartridge.

Ion-Ex Cartridge contains a "mixed bed" of strong acid and strong base ion exchange resins. The "mixed-bed" technique provides efficient and complete deionization in a single column. The cartridge is disposable so that regeneration is not required, eliminating such problems as organic fouling, breakdown due to oxidation, maintenance of equipment.

Millitube-MF Cartridge contains Millipore filter material which removes all suspended particles and microorganisms larger than filter pore size (typically 0.45 or 0.22 micrometers) from water flowing through. Millipore filters are unique in having an "absolute" rating.

Super-C Cartridge contains a bed of granulated activated carbon which removes dissolved organic contaminants from water flowing through. The use of this disposable cartridge is recommended when the presence of organic contamination in water is suspected.

MASTER MODULE

This control unit responds to a signal from a resistivity sensor and either sends water to recirculation or to drain if its quality falls below a pre-set level, such as 0.5, 1.0 or 5.0 megohm-cm. The Master Module includes a 3-way valve, electronics and resistivity set point control. It also includes a resistivity sensor when supplied with systems which do not include Hydronomic rinse tanks or where rinse tanks are supplied without covers, and a remote-mounted meter for measuring the resistivity of rinse effluent to determine when rinsing is complete.

RINSE TANKS
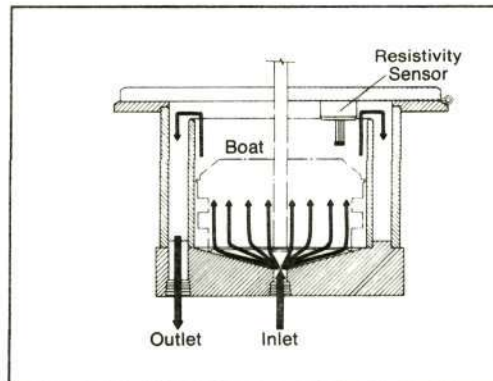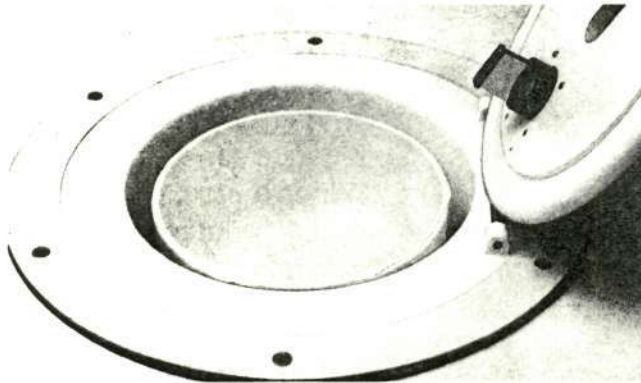
Hydronomic rinse tanks are designed so that all contamination coming off the wafers is carried up and out of the tank. A hinged top protects against "fall-out" contamination. A sensor in the cover of the tank measures the resistivity of water *after* rinsing so that boats of wafers can be removed as soon as downstream water is 18 megohm-cm. This eliminates waiting for an arbitrary "elapsed time," shortens rinse cycles and increases production capacity. Rinse tanks are also supplied without covers in which case the sensors are located in the Master Module. The flow rate in each tank is up to 2.5 gpm.
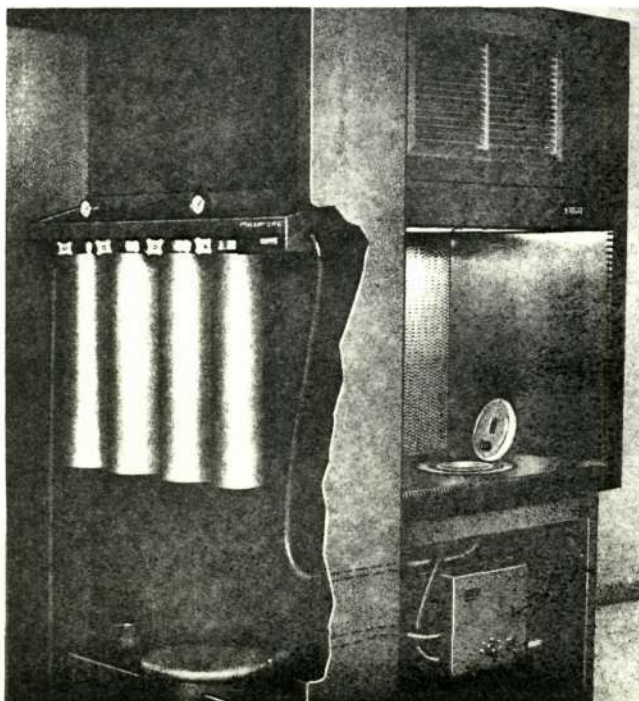
How Hydronomic modules can be incorporated into an existing wafer washing station.

Hydronomic Systems

The Modular Approach Towards Fulfilling Particular Wafer Washing Needs

Hydronomic modules can be assembled in various combinations and configurations to fit the specific requirements of existing wafer washing stations. For instance, the dimensions of the Master module will permit installation in existing limited-space work stations. The pump/reservoir and Super-Q System can be mounted externally, allowing for installation in a maintenance aisle to keep the work area free during normal maintenance procedures. Three typical installations are described on these pages. Complete wafer washing stations, incorporating Hydronomic capability, are also available and are described on the following two pages.
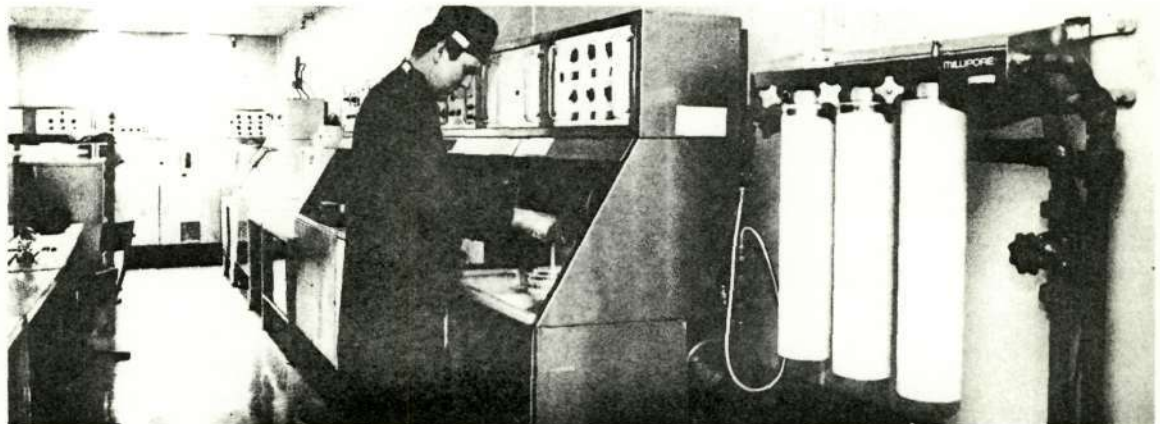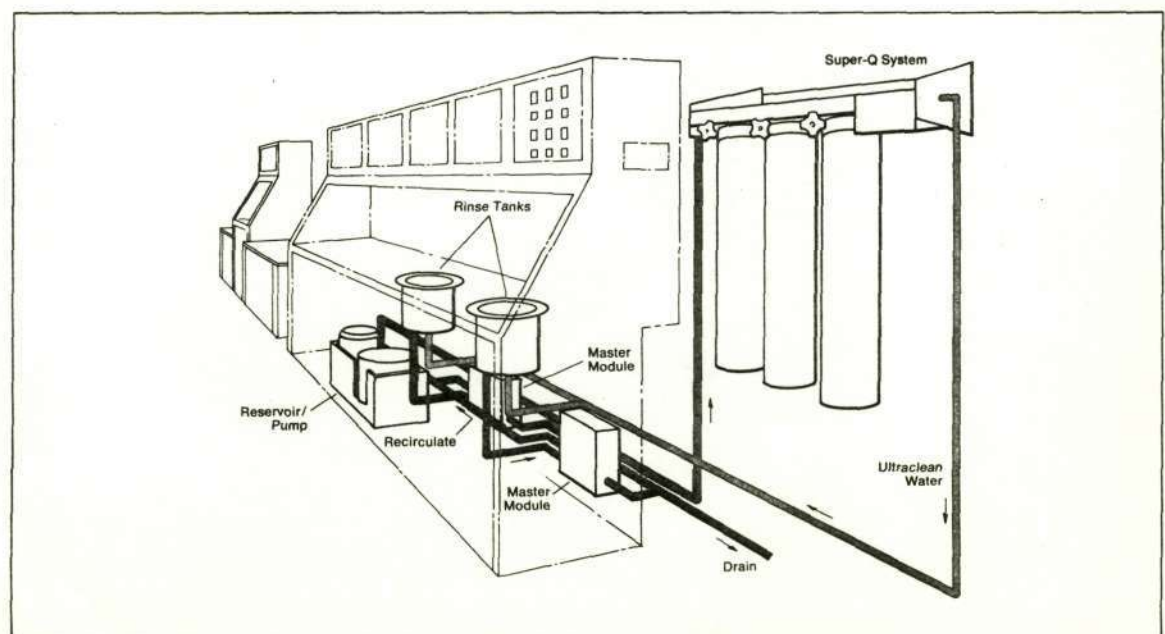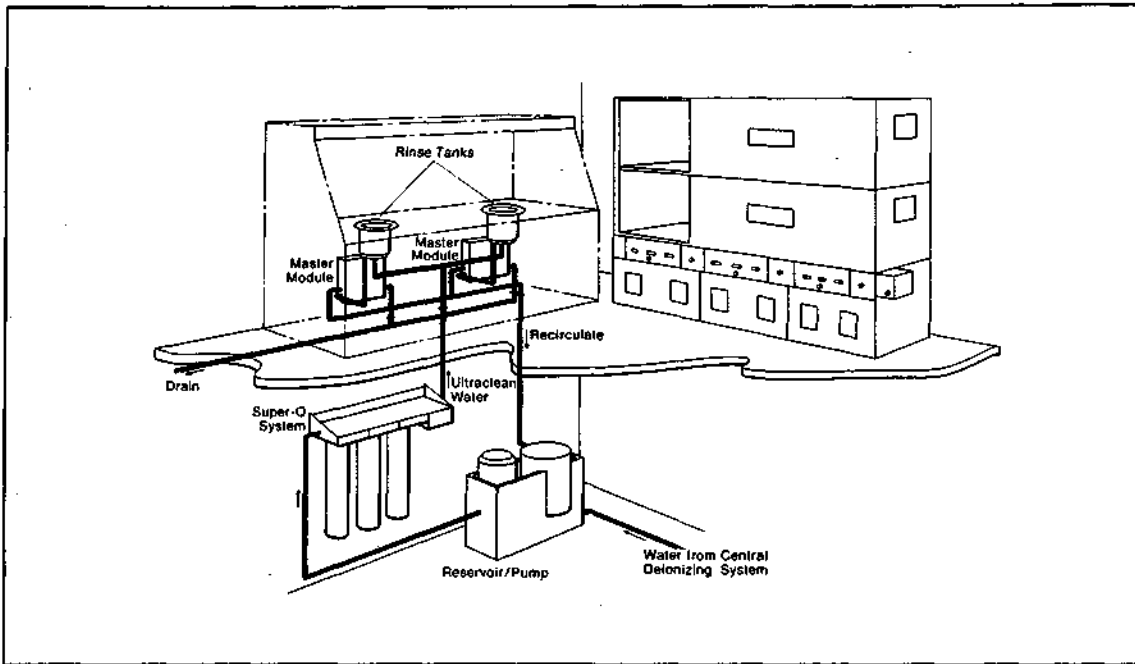

Photo courtesy of Texas Instruments Limited, Bedford, England

How a Hydronomic system could be installed in an existing microcircuit production facility.

Reservoir/Pump and Super-Q System in room below typical installation of Hydronomic rinse tanks and Master modules in a microcircuit production facility. This arrangement segregates routine maintenance activities, e.g., the changing of Super-Q cartridges, from device manufacturing area. Also, replacement cartridges for the Super-Q System can be stored nearby.
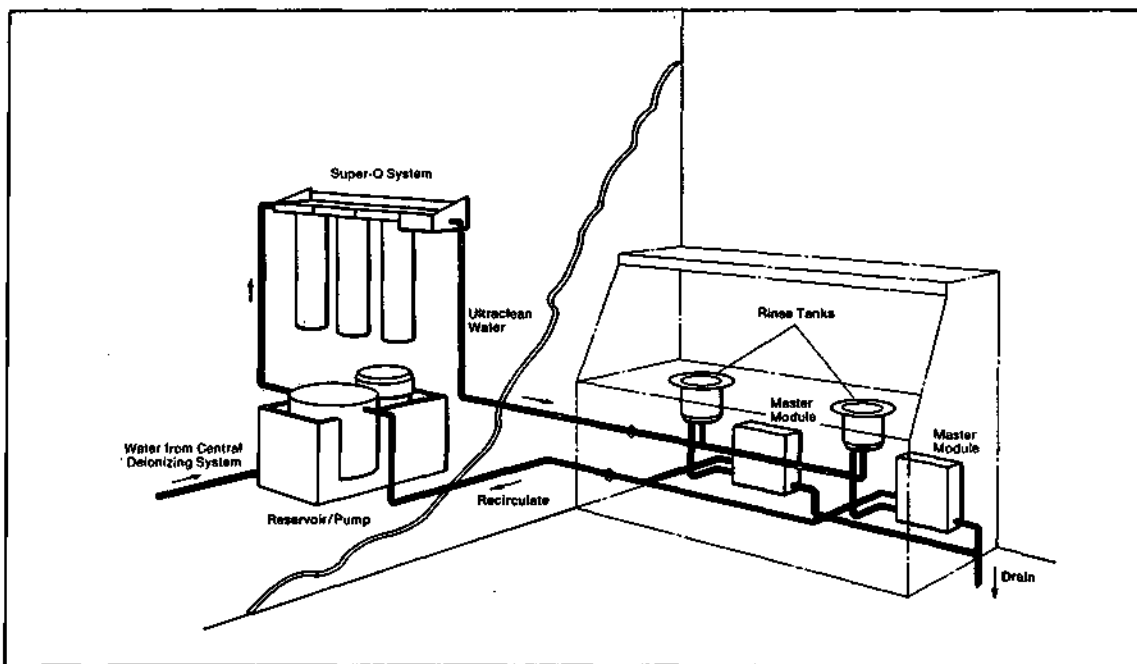

Typical installation with Super-Q System and Reservoir Pump in the maintenance aisle of a microcircuit production facility. Like the above plan, this installation separates Hydronomic components requiring routine maintenance from the proximity of microcircuit production facilities.

7

Hydronomic Wafer Washing Stations

**Complete, Independent Semiconductor Wafer Washing Installations
For use in Open Manufacturing Areas or Class 100 Clean Rooms**

Millipore Hydronomic wafer washing stations incorporate all components necessary to efficiently cleanse semiconductor devices. A Millipore Super-Q System provides high-purity water to two rinse tanks. Each rinse tank provides a flow rate of 2 gpm. Depending on its quality, effluent water from the tanks is either conserved and reprocessed by the Super-Q System or discarded to drain. The operator may set this decision point at 0.5, 1.0, 2.0 or 5.0 megohm-cm. A meter in the effluent line of each tank indicates when the rinsing cycle is complete.

Because warm water has been found by some companies to increase washing effectiveness and therefore reduce the rinsing time required to clean semiconductor devices, Hydronomic wafer washing stations incorporate a built-in heating system to maintain water temperature, preset anywhere between ambient and 130°F.
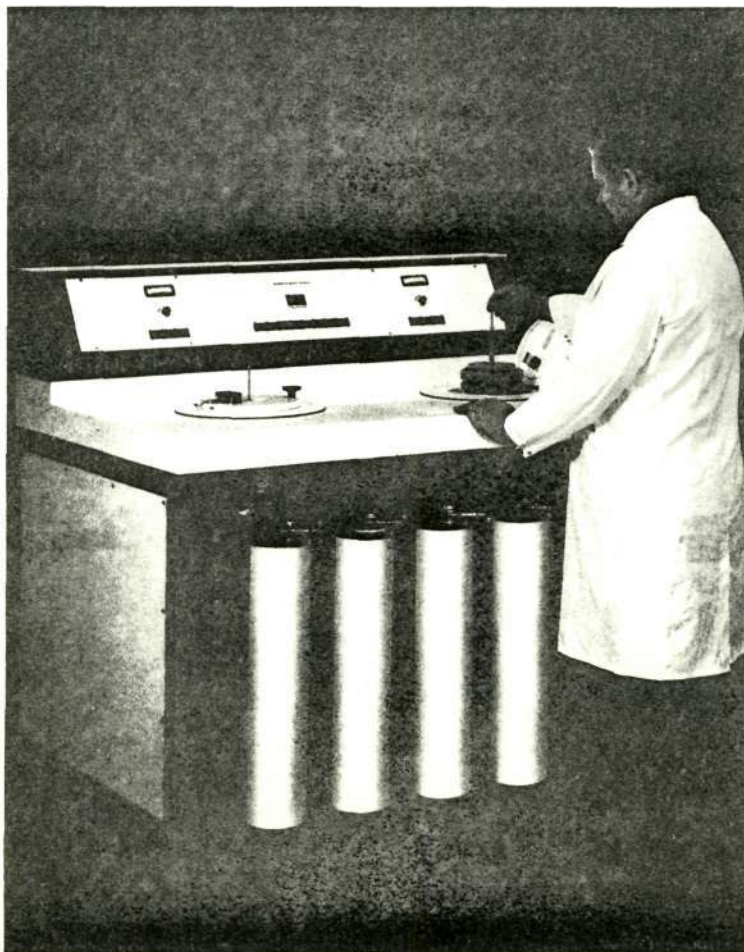

Model 2
For Use in Class 100 Clean Rooms

This station comprises two rinse tanks, a Millipore Super-Q System, and three resistivity meters for monitoring water quality, before and after washing. The two rinse tanks are mounted on a bench level work space, and the electronic controls are located on a sloping panel at the rear of the bench top facing the operator. Rinse tank modifications can be made.

Model 1
For Use in Open Manufacturing Areas

This washing station is basically the same as the one described above except that it includes, in addition, a class 100 laminar flow hood, complete with operating controls.
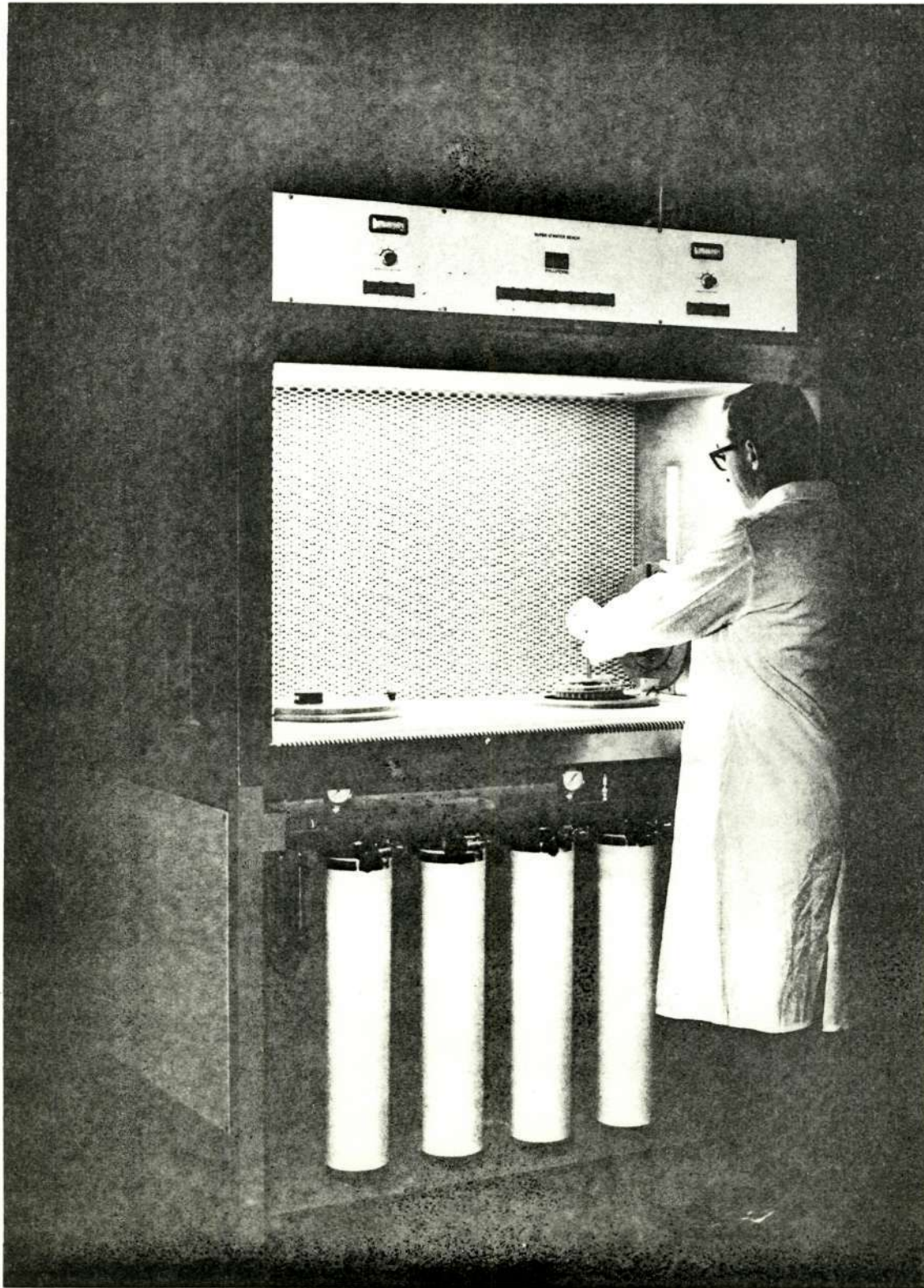
Hydronomic Performance

Conventional semiconductor device manufacturing operations depend on centralized plants to remove dissolved and suspended contaminants from raw water. This treated water is then piped around the manufacturing area in a recirculation loop, back to the upstream side of the final mixed bed ion-exchange columns. To avoid water deterioration in stagnant lines, all rinsing stations in the manufacturing area are fed from the recirculation loop on short lengths of pipe and left running continuously whether devices are being rinsed or not.

All of the high-quality water not used for rinsing is therefore wasted. Even during a normal 15 minute rinsing cycle, as much as 80% of the water discarded can be of one megohm-cm quality or better. This water could be reprocessed at a cost of 0.1 cent per gallon, just 10% of the industrial average for production of high-purity water from raw water.

Figures 1 to 4 illustrate the performance of Hydronomic systems applying various rinsing schemes which were evaluated by a semiconductor device manufacturer. This study was made to find an alternative to the conventional method which consisted of moving a basket of wafers through three stations of a cascade rinser flowing at 1.5 gpm for a total of ten minutes. The basket was finally placed in a spray rinser flowing at 1 gpm for five minutes. Total water used in this process was 20 gallons, and even after such a rinse, placing the basket in a Hydronomic system caused the resistivity meter on the effluent line to indicate incomplete rinsing. A further 30 seconds was required before the effluent meter read 18 megohm-cm consistently.

Figure 1 charts the quality of effluent water from a 2.4 gpm Hydronomic rinse tank into which a basket of wafers was placed following a chromic acid bath and a 60 second quench in a 1 gpm cascade rinser. Note that after two minutes, effluent water quality reached better than 6 megohms, and after a period of five minutes rinsing was complete. The total volume of water discarded was only 3.4 gallons, the balance being reprocessed by the Super-Q System. Figure 2 shows much more rapid clean-up time. However, the basket of wafers was spray-rinsed for 3 minutes prior to being placed in the Hydronomic system.

Figure 3 shows the rinsing clean-up curves for a basket of wafers placed in a silicon oxide etch consisting of one part hydrofluoric acid to 10 parts saturated ammonium fluoride.

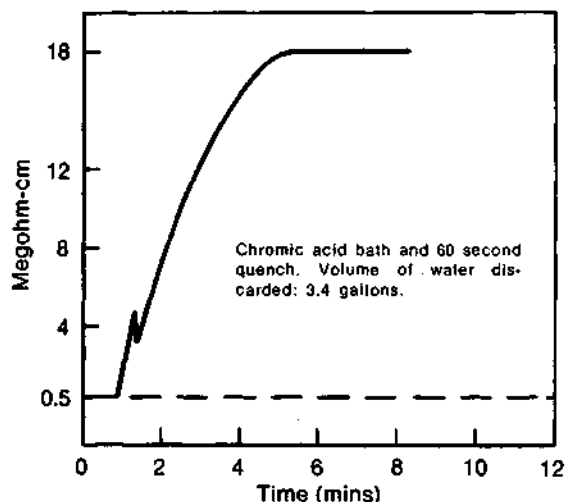Significant technical and economic advantages accrue to the manufacturer that employs Hydronomic systems:

Fig. 1

Advantages of Hydronomic Rinsing

a. Operators know definitely when rinsing is complete by reading the meter which monitors rinse-tank effluent quality. During one study, a rinsing cycle curve such as Figure 4 occurred in certain instances. The reason — small pieces of broken wafer material adhering to the basket and other wafers were trapping traces of acid. The diffusion of acid away from these areas was very slow, prolonging the rinse cycle. Normally this condition would not be noticed in a conventional system and the basket would be removed before rinsing was in fact complete.

b. Eighty percent of total rinse water now discarded is reprocessed to high-purity. At 10% of the average industrial cost of producing high-purity water from raw water, the net savings from two rinse tanks would be a minimum of $4,000 for a single year. More likely this figure should be closer to $5,000 since rinse tanks are never utilized continuously for rinsing.

c. Processing all rinse water to a constant level of high-purity at the point-of-use by the Super-Q System avoids water quality degradation that always occurs in the pipelines. This eliminates the situation of getting water of resistivity below 10 megohm-cm with unacceptable levels of particulate and microbial contamination in the rinse tank while producing 18 megohm-cm water at the centralized plant.

Hydronomic systems increase the consistency and performance of rinsing semiconductor devices by applying terminal processing. Pay-back time is less than 12 months.
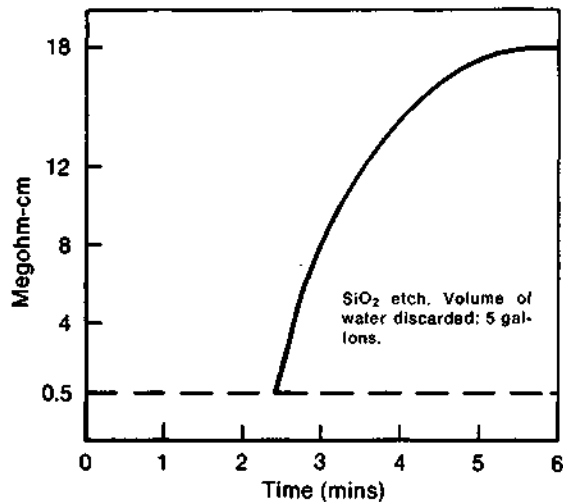
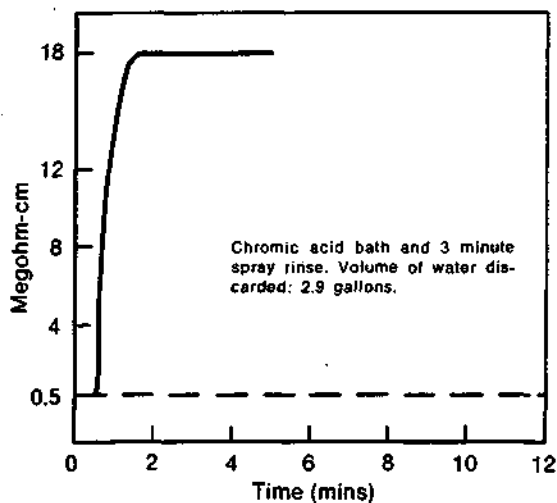SiO$_2$ etch. Volume of water discarded: 5 gallons.

Fig. 3

Chromic acid bath and 3 minute spray rinse. Volume of water discarded: 2.9 gallons.

Fig. 2

SiO$_2$ etch and 15 second quench. Volume of water discarded: 1.25 gallons.
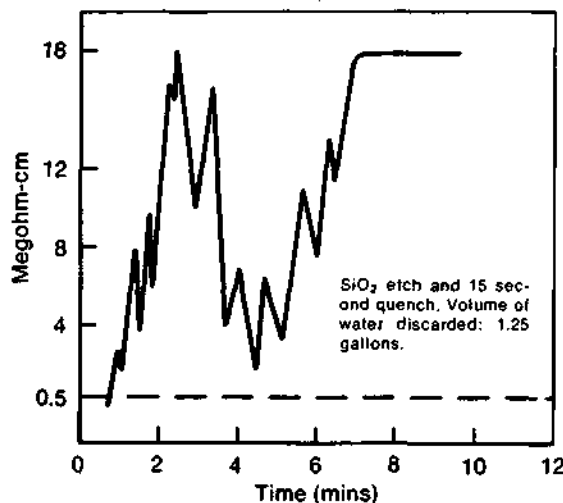
Fig. 4

Application Evaluation and System Recommendation

To help you determine how the Hydronomics concept can be applied to your advantage, Millipore will work with you to analyze plant requirements, and then "custom-engineer" a system that best meets them.

While the systems described in this bulletin are the basis of our recommendations, modifications and variations can be made to suit particular needs.

The economics of system operation in your plant under your conditions will be estimated in our report and, where possible, a comparison with alternative methods will be included.

This Millipore technical service is available free of charge and may be obtained by contacting one of our offices shown on the opposite page.

1. Camenzind, Hans R., *Electrotechnology*, February 1968, pp. 50-64.
2. Simon, G. P., and Calmon, C., *Solid State Technology*, February 1968, pp. 21-30.
3. Peruffo, Joseph D., *Industrial Water Engineering*, April 1966, pp. 12-17.
4. Central system cost from paper by Covert F. Smith, The Permutit Company entitled "Fifteen Years Experience in the Production of Ultrapure Water for the Microelectronics Industry," given at the 7th Annual Liberty Bell Corrosion Course and published jointly by the Philadelphia Section, National Association of Corrosion Engineers and Drexel Institute of Technology.

Fluoroflo RD70A
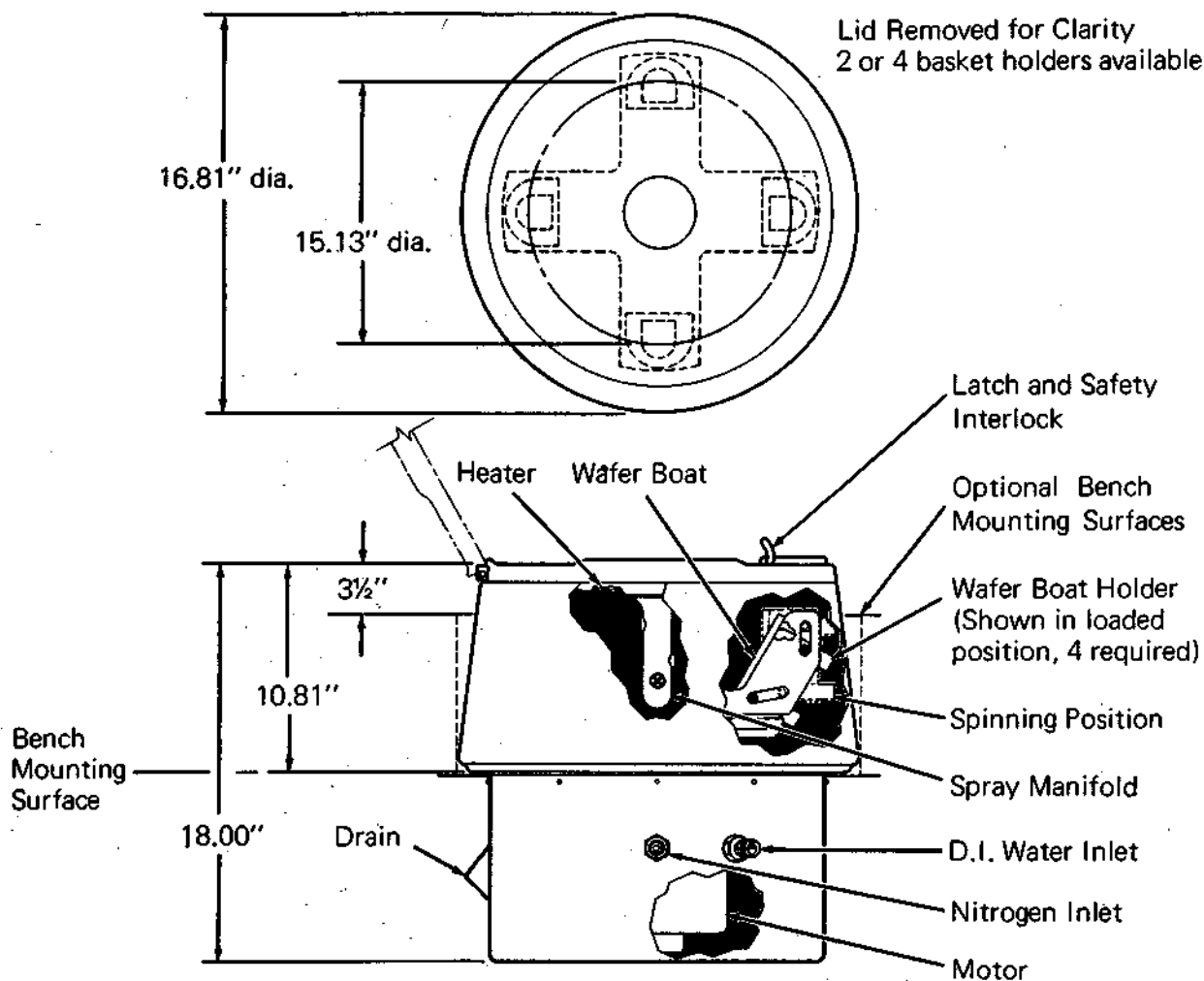# Rinser Dryer

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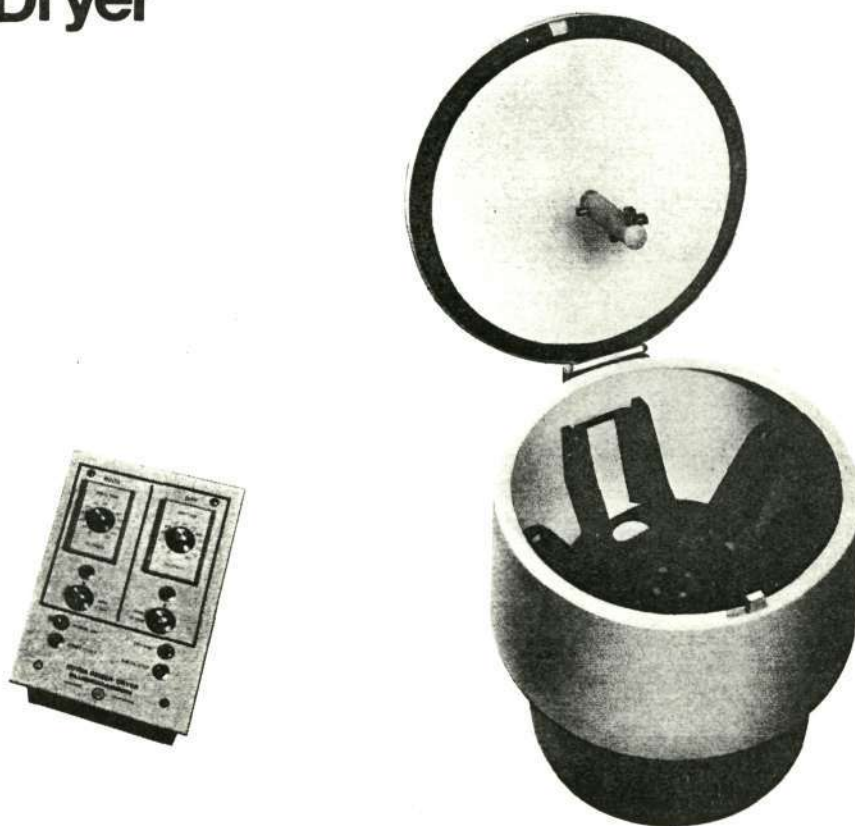
RD70 DESIGN FEATURES

RD70A provides the utmost in final batch processing of semi conductor wafers and micro-electronic substrates.

Centrifugal force places the wafers/substrates in a horizontal position thereby inducing a "slicing" action. This action delivers immediate and complete fluid runoff. The force acts through the strong axis of the wafer to eliminate the possibility of breakage.

Rinsing is accomplished through four unidirectional jet spray nozzles manifolded on the lid deflector. All Teflon® components are used to handle the fluid media.

Drying is accomplished by introducing dry nitrogen through the same nozzle system.

Adjustable solid state timers and speed controls monitor customer desired level of operation.

Lid Removed for Clarity
2 or 4 basket holders available

16.81" dia.

15.13" dia.

Latch and Safety Interlock

Heater   Wafer Boat

Optional Bench Mounting Surfaces

Wafer Boat Holder (Shown in loaded position, 4 required)

3½"

10.81"

Spinning Position

Bench Mounting Surface

Spray Manifold

18.00"   Drain

D.I. Water Inlet

Nitrogen Inlet

Motor

RD70A PHYSICAL OUTLINE

Specifications:

Rinse Speed Range	0 — 500 rpm	0 — 30 psi Nitrogen
Dry Speed Range	0 — 2200 rpm	0 — 30 psi DI Water
Rinse Time	0 — 120 sec	
Dry Time	0 — 120 sec	
Weight	75 lbs	

Designed to operate on 115 VAC
Single phase, 60 cycle power.

Powered by ¼ horsepower
industrial Bodine motor.

Installation: Simply bench mount or place on station top. Controls are remote. Connect DI water and nitrogen supply (recommend 20 psi). Drain tube is 1½" diameter, and must be vented to atmosphere.

Operation: Automatic two step cycle. Insert baskets, close safety latch, and press start button.

How to order: Part Number — RD70A (complete with rinser) Spindle and Basket Holder separate (specify requirement)

Model (Part No.)	RD70A	2-Basket Holder	4-Basket Holder
Price	$1725.00	$250.00 (specify size basket)	$450.00 (specify size basket)

The RD70A rinser-dryer unit is part of a system of wafer handling equipment. Several carrier designs and accessories are available. Basket holders can be adapted to handle other "box" type or "round" carriers. Please consult our factory for custom engineered requirements.